Journal of the Royal Society of Western Australia

ISSN 0035-922X

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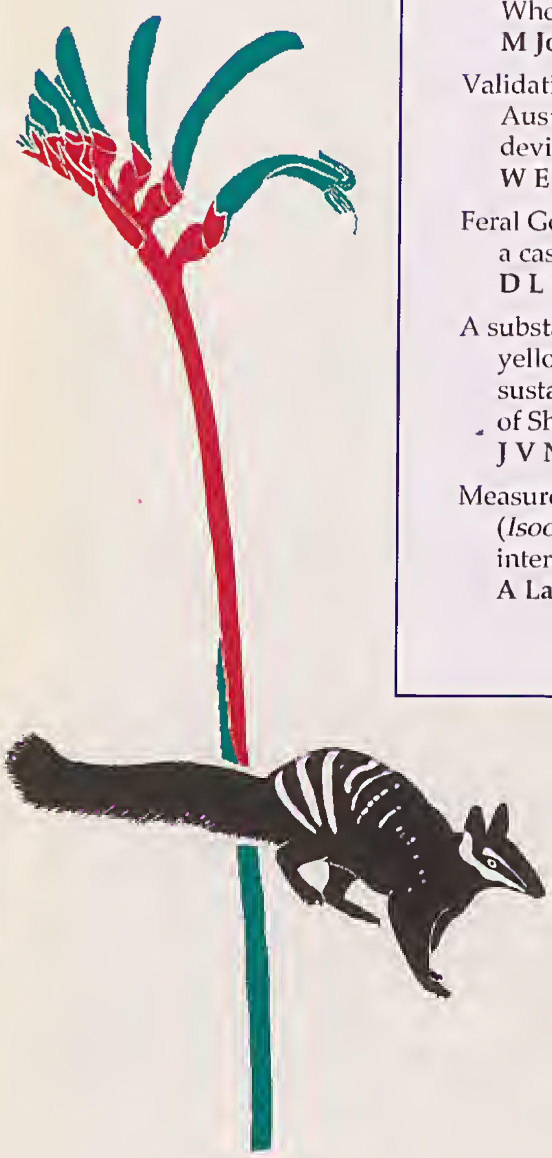
Volume 90 Part 3
September 2007



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Cover design: The four subjects symbolize the diversity of sciences embraced by the Royal Society of Western Australia. Mangles' kangaroo paw (*Anigozanthos manglesii*) and the numbat (*Myrmecobius fasciatus*) are the floral and faunal emblems of Western Australia, and stromatolites are of particular significance in Western Australian geology (artwork: Dr Jan Taylor). The Gogo Fish (*Mcnamaraspis kaprios*) is the fossil emblem of Western Australia (artwork: Danielle West after an original by John Long).

Journal of the Royal Society of Western Australia, 90: 115–125, 2007

Description of grinding patches found on granite bedrock near Cue, in central Western Australia, and a discussion of their significance

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Manuscipt received November 2005; accepted June 2007

Abstract

Patches of exposed granite bedrock around Cue, in central Western Australia, that have been smoothed by being used for grinding are described and compared with portable grindstones recorded in the same region. Patches had rarely been reported from this area before, although they have long been recognised in the Pilbara. The extension into the southern half of Western Australia of a type of evidence for past human behaviour rarely identified there is significant. Two much-debated questions are also considered, but left unresolved due to insufficient data: whether there is a morphological difference between grindstones used to wet mill grass seeds and those used for dry grinding hard seeds and whether the juxtaposition of grinding, generally considered to have been women's work, with rock carvings, usually assumed to have been made by men, is socio-culturally significant.

Keywords: grinding patches, granite bedrock, Cue, central Western Australia

Introduction

Grinding patches can be defined as 'rock pavements or slabs worn smooth by Aborigines grinding on their surface ... they are most commonly found in arid regions, where Aboriginal people, especially women, carried out seed grinding' (Flood 1990). Elsewhere in the same text, she was more specific about what was ground. Grinding patches were 'oval patches of rock worn smooth from women's grinding of grass seeds into flour' (Flood 1990). Later, she widened her definition. A grinding patch became 'a concave abraded hollow on a horizontal or sloping rock surface, usually produced by grinding ochre or foodstuffs such as hard fruits' (Flood 1997).

Flood (1990) also noted that grinding patches are frequently located near petroglyphs (engraved rock art motifs), being found 'close to or even on top of engravings'. For example, in the Pilbara, 600–750 km north of Cue, there are grinding patches at art sites on Gallery Hill, Woodstock (Flood 1990). At Spear Hill, 'there are many seed-grinding patches on the pavements and aprons at the base of conical hills' (Flood 1990). While, on the Burrup Peninsula, there are 'patches of rock worn smooth by grinding by Aboriginal people, usually women, grinding acacia or grass seeds into flour' (Flood 1990).

Later, Flood (1997) stated firmly that grinding patches 'are utilitarian by-products of grinding up foodstuffs, ochre or other commodities'; emphasising that they 'are economic, functional marks left by grinding activity usually on horizontal surfaces or large portable rock slabs. Residue analysis has shown that some grinding hollows were used for pulverising ochre and some for grinding up food substances such as hard fruits. [They] are utilitarian marks which should not be classed as rock art'.

Other authors also emphasise the utilitarian nature of grinding patches. 'Domestic camping activities are evident at sites [around Dampier], particularly grinding patches on the rock where grass-seed flour was made, which was a woman's task; sometimes the grinding occurs between engravings' (Mulvaney and Kamminga 1999). These sites are: Skew Valley, Gum Tree Valley and Kangaroo Valley, studied by Lorblanchet (1992).

The identification in October 2004 of grinding patches on five granite outcrops located within a 50 km radius of Cue (Gunn & Webb 2006), a small town on the Great Northern Highway in central Western Australia (Figure 1), is reported here. At one site, petroglyphs flanked the grinding patches. Such patches, particularly juxtaposed to rock art, had rarely been reported from this area before, although hundreds of patches, with and without artwork, are known further north, particularly in the Pilbara.

Patches can be extremely difficult to see, those reported on here were identified as much by touch as by sight. They are described in this paper in the hope that more may be recognised and reported on in the Murchison-Gascoyne region in future by other researchers. The socio-cultural implications of the geographic distribution of such features in Western Australia and their occurrence close to rock art are then considered. Whether or not there is a morphological difference between grindstones used to wet mill grass seeds and those used for other tasks is also discussed.

Site descriptions

In total, 43 grinding patches were found at six sites in the study area: Afghan Rock, Boat Hole Rock, Camel Soak, *Djungari*, Pool Paddock and Taincrow Rockhole.

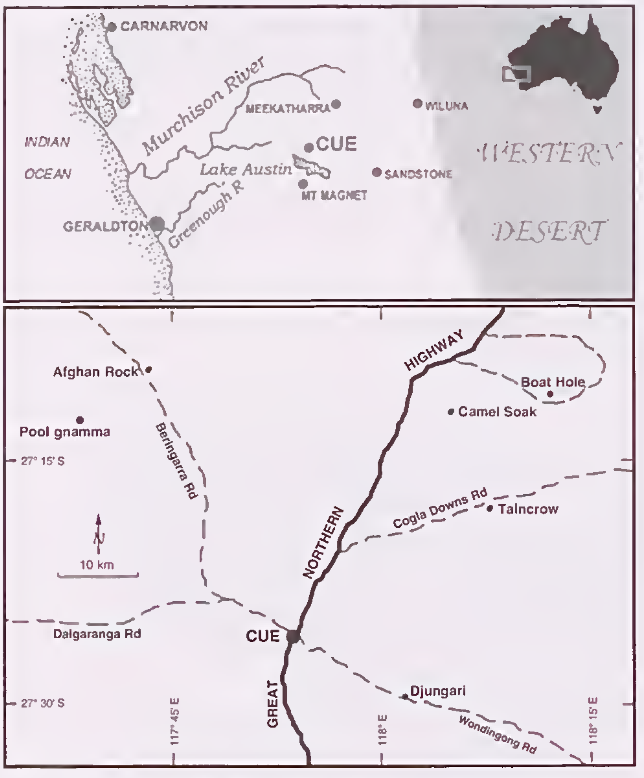

Figure 1. Location of the study area (drawn by AM Rossi).

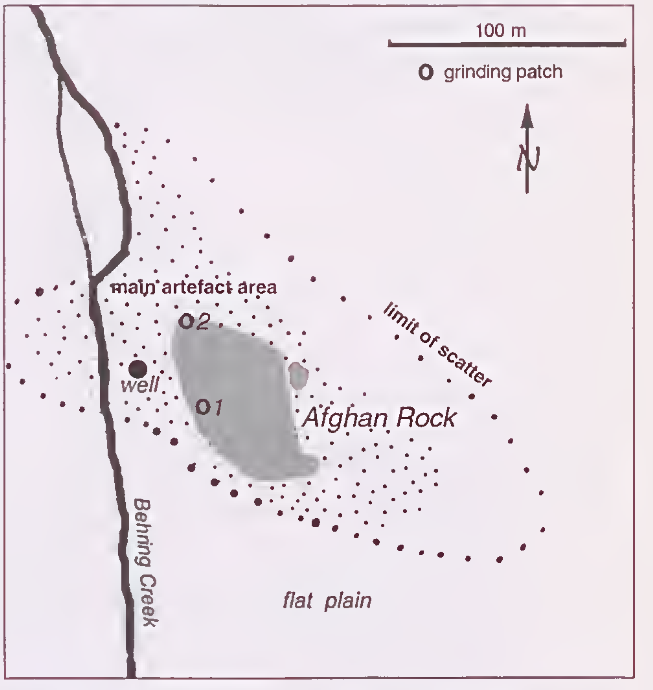

Figure 2. Archaeological features recorded at Afghan Rock (adapted by AM Rossi from an original by RG Gunn).

The dimensions of all the patches that could be measured are listed in Table 1. The numbers in this table correspond with the patch numbers in Figures 2–6.

Afghan Rock

Afghan Rock is a small granite dome, some 80 m x 40 m in area, that rises about 20 m above the surrounding plain, 500 m north of the road from Cue to Beringarra, about 11 km south of The Glen homestead. The dome has a number of large shallow pans on its crest that hold water after rain. According to the present lessee, the well (Figure 2), which is now powered by a wind pump, was originally dug by Afghan cameleers who camped at the rock in the 1880s and gave the place its modern name. There is an extensive scatter of Aboriginal stone artefacts around the dome and beside Behring Creek (Gunn & Webb 2003), suggesting that the Afghan well may have been dug into an Aboriginal soak.

Two grinding patches were located on this dome, about 30 m apart (Gunn & Webb 2006): one on the western side and one on the northern tip (Figure 2). Both are on subhorizontal surfaces close to the soak, about 0.5 m above where the bedrock emerges from the surrounding colluvium. Patch 2 was particularly difficult to see; it is poorly developed.

Boat Hole Rock

Boat Hole is a gnamma (rockhole) that has formed on the crest of a low granite outcrop, located some 13 km east of Tuckanarra, 500 m north of the road to Reedy town site. The gnamma is a pointed oval 6.0 m long, 2.3 m wide and at least 0.5 m deep; its capacity is estimated at 6750 L. Gunn & Webb (2006) located seven grinding patches on the bedrock around the gnamma: patches 1 and 2 are on the edge of gnamma, 3 is nearby, while patches 4–7 are on the edge of the outcrop (Figure 3). Patches 6 and 7 could not be measured because the bedrock on which they formed is now broken. None of these patches is well-used, but all were quite easy to see.

Camel Soak

Camel Soak is a well-vegetated depression beside a large, low granite dome. It was a watering point for cameleers using the old road from Cue to Meekatharra.

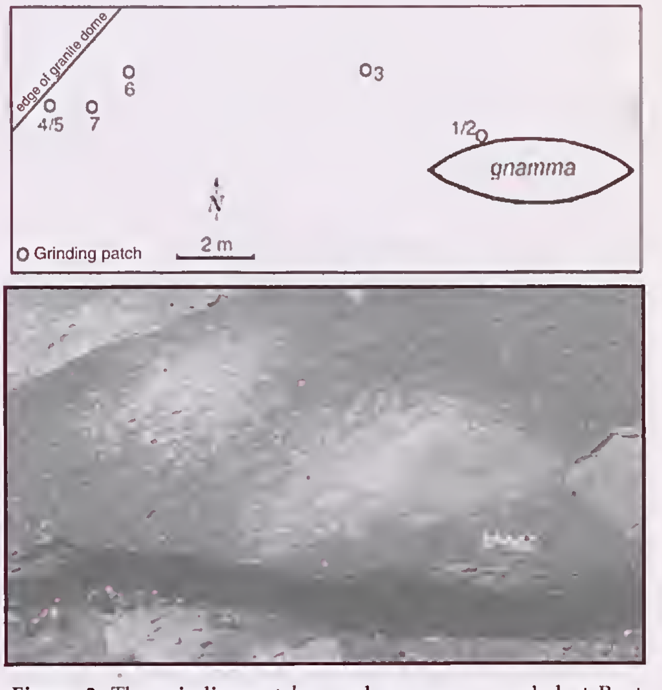

Figure 3. The grinding patches and gnamma recorded at Boat Hole Rock (adapted by AM Rossi from an original by RG Gunn). Patches 4 and 5 are pictured (photo: RG Gunn).

The dome lies east of the Great Northern Highway, 2 km south of Tuckanarra and south of the road to Reedy. The depression is probably an enlargement of a pre-existing Aboriginal soak. It appears to be fed by precipitation running off the adjacent dome. The soak's original dimensions are unknown, but that it may have held a considerable volume of water in the past, is suggested by the dense artefact scatter (40–50/m²) that now covers an area about 300 m x 250 m around the depression (Figure 4 top). The size of this scatter suggests that the area was either visited frequently for short periods, or intermittently for longer periods, by unknown numbers of people.

Five petroglyphs and 14 grinding patches were found, about 20 m from the soak, in an area 10 m by 5 m where the granite emerges at a shallow angle from the present ground surface (Figure 4 bottom). Patch 8 could not be measured because the bedrock on which it formed is now broken. The long axes of patches 1, 6 and 10 are transverse to the slope of the bedrock; that of the others, parallel. The surface on which they have developed is subhorizontal.

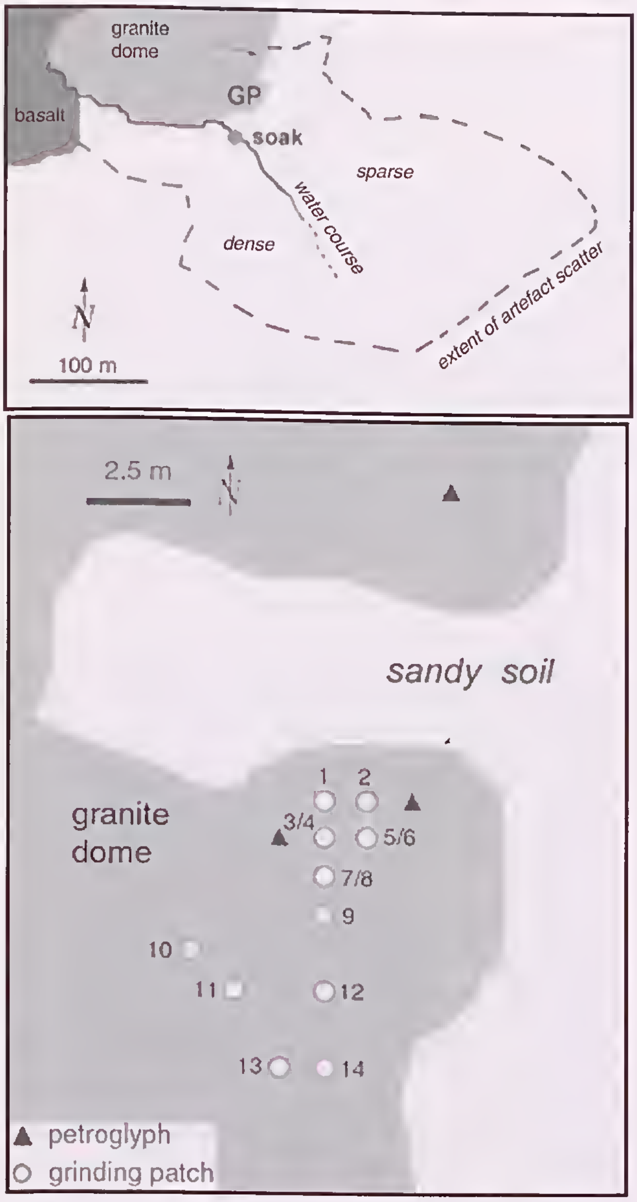

Figure 4. Archaeological features recorded at Camel Soak, with details of the grinding patches (GP) and petroglyphs (adapted by AM Rossi from an original by RG Gunn).

These are the first petroglyphs made on an open granite pavement found in this region, although well-patinated petroglyphs were found on a dolerite dyke 70 km northwest of Cue (Gunn & Webb 2003). Most of the other petroglyphs recorded in this region were made in rockshelters or on protected vertical walls (Gunn & Webb 2000, 2002).

The petroglyphs flanking the grinding patches comprise, west of patches 3–4, a pair of pounded half-patinated emu footprints and a fragment, and a pair of unpatinated abraded macropod tracks, east of patch 2 (Figure 4). Another, isolated, pair of macropod tracks was found 6 m to the north of the grinding patches.

The grinding patches and petroglyphs at Camel Soak are patinated to a similar degree, suggesting that they were made penecontemporaneously and should probably be viewed as a 'set'. Such juxtapositions have rarely been recorded in the southern half of Western Australia. They are discussed further below because they raise the issue of who made what. In the report on this site, we noted that 'the association of grinding patches with petroglyphs is well known in the Pilbara, where it is generally accepted that the patches were probably made by women, while the petroglyphs were probably made by men' (Gunn & Webb 2006).

While these patches and petroglyphs are likely to be of similar age, when they were made is not known because no temporally diagnostic 'formal tools' were noted in the area of the artefact scatter selected for analysis (Gunn & Webb 2006). A quartz flake with some edge retouch was identified, but could not be classified further and is chronologically uninformative.

Djungari

Djungari, also called Garden or Bald Rock, is a prominent granite dome about 1.5 km in diameter that lies about 20 km east of Cue, just north of the road to Sandstone. It is known to have been a traditional campground; rainwater collects in pans on the dome and the surrounding vegetation provides shade, shelter and food. At the northwestern end of the dome, near an ephemeral creek, there are two wells of European construction (Figure 5 top). A fairly dense and extensive artefact scatter was noted across the creek from the wells (Gunn & Webb 2002), suggesting that the wells may be sited near an Aboriginal soak. The area around *Djungari* is very rich in archaeological sites, some of considerable ceremonial significance (Gunn & Webb 2002). That more sites await rediscovery in this area is shown by the fact that five grinding patches have now been identified on the western edge of the dome adjacent to the creekline (Gunn & Webb 2006). All are on horizontal surfaces only a few millimetres above the ground surface and less than a metre from the edge of the dome (Figure 5 bottom). No grinding patches were found near any of the gnammas known in the surrounding area, despite a careful search.

Pool Paddock

Pool Paddock on Coodardy pastoral lease, northwest of Cue, contains a gnamma measuring 2.6 m x 1.8 m x >

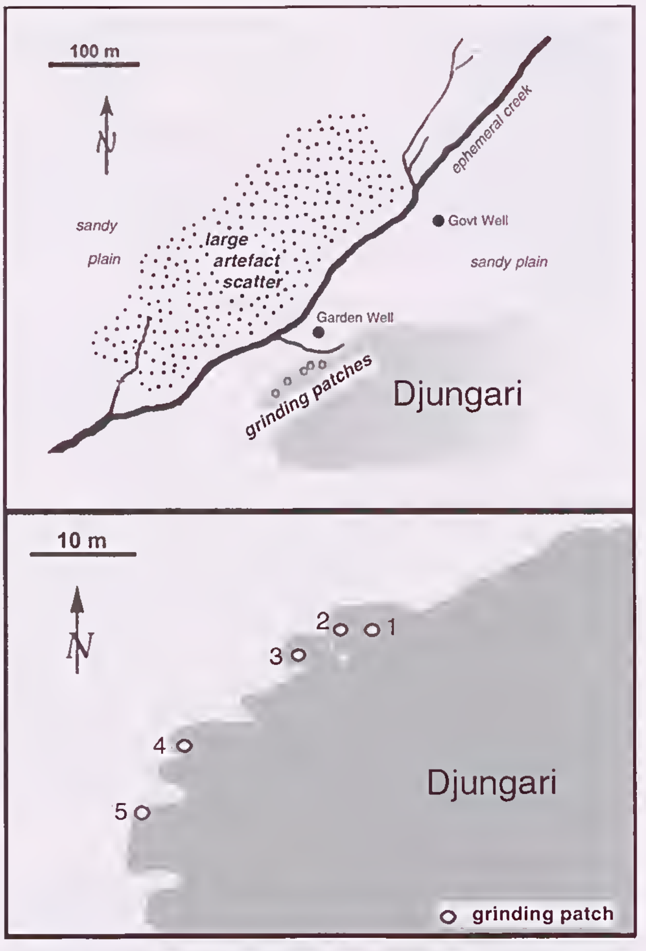

Figure 5. Archaeological features recorded at *Djungari* dome and details of the grinding patches (adapted by AM Rossi from an original by RG Gunn).

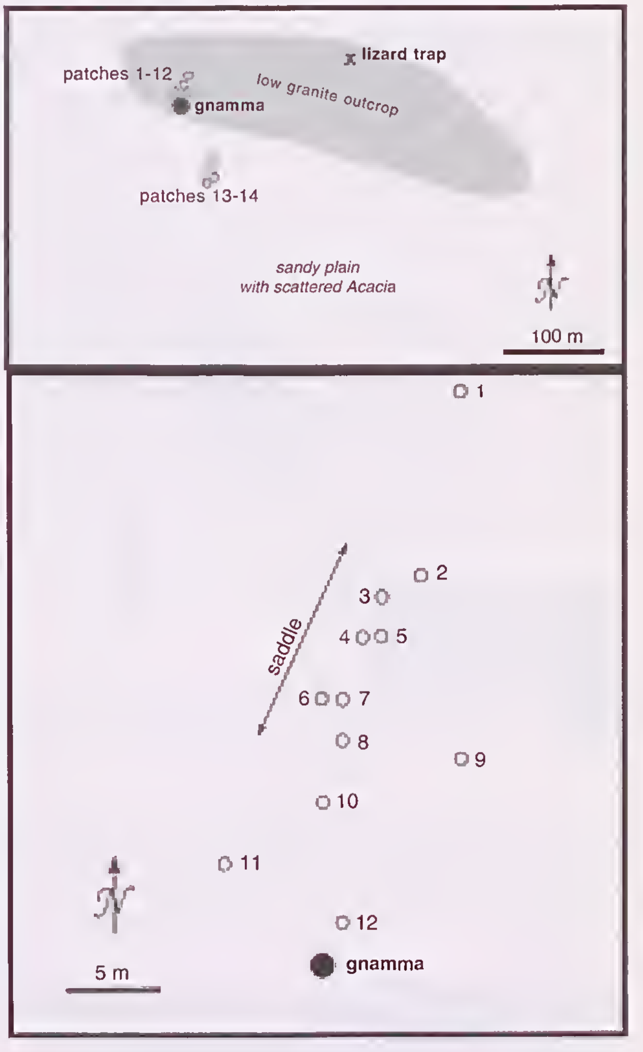

Figure 6. Archaeological features recorded around Taincrow Rockhole and details of grinding patches 1–12 (adapted by AM Rossi from an original by RG Gunn).

1.5 m with an estimated capacity of at least 6000 L (Gunn & Webb 2003). This gnamma has formed in an inconspicuous granite pediment. Very few artefacts were noted on the ground around the gnamma, but a grinding patch, measuring 400 mm x 200 mm, has developed on its eastern rim, indicating that Aboriginal people camped near this water source in the past. The significance of this patch was not appreciated when it was recorded in 2002 because it was an isolated find. This site is located about 7 km southwest of Afghan Rock and can now be seen to belong to the suite of sites described in this paper.

Taincrow Rockhole

Taincrow gnamma measures 3.0 m x 2.3 m and is at least 1 m deep, an estimated capacity of 5000 L. It has formed on the west side of a low granite outcrop (Figure 6 top). A cluster of 12 grinding patches was found on the flat or slightly sloping surface of the granite within 30 m of the gnamma (Figure 6 bottom); patch 1 is on the upper surface of a 1.2 m long block of granite resting on bedrock (Gunn & Webb 2006). Patches 13 and 14 were found on a separate inconspicuous pavement, 100 m to the south of the gnamma and barely emergent from the surrounding colluvium.

A lizard trap was also identified on the north side of the outcrop housing the gnamma (Figure 6 top). It is the first, and as yet *only*, lizard trap found near Cue (Webb in press). All the lizard traps recorded to date in Western Australia are made from and positioned on granite, however. It is possible, therefore, that further traps may await identification around Cue, which is located on the Archaean granites of the Yilgarn Craton (Myers & Hocking 1988).

Summary

The 14 grinding patches found at Taincrow Rockhole were the first noted east of Cue by Gunn & Webb (2006). Subsequently, we found 14 patches at Camel Soak and seven at Boat Hole Rock; also on granite outcrops east of Cue. This plethora of a type of evidence of past Aboriginal activity, previously only noted at Pool gnamma (Gunn & Webb 2003), west of Cue, prompted us to re-visit some of the other granite domes and outcrops in the region to see whether they hosted grinding patches that we had overlooked during previous surveys. As a result, two grinding patches were found at Afghan Rock and five at *Djungari* (Gunn & Webb 2006). All told, 43 patches have now been recorded at six sites within a 40

Table 1

Dimensions in millimetres of all the measurable grinding patches noted at granite exposures around Cue (Gunn & Webb 2006). The patch numbers match those in Figures 2–6.

patch	Afghan Rock	Boat Hole	Camel Soak	Djungari	Pool Pddck	Taincrow
1	260 x 170	300 x 160	750 x 600	230 x 130	400 x 200	200 x 120
2	360 x 260	250 x 160	250 x 150	280 x 220		150 x 100
3		520 x 280	380 x 150	400 x 200		270 x 230
4	"	650 x 450	270 x 170	200 x 180		210 x 150
5		500 x 320	500 x 250	310 x 290		350 x 250
6		broken	550 x 300			200 x 120
7		broken	400 x 220			250 x 140
8			broken			350 x 200
9			350 x 350			300 x 250
10			330 x 200			170 x 120
11			340 x 220			160 x 120
12			400 x 250			350 x 220
13			660 x 350			350 x 180
14			380 x 300			280 x 180

km radius of Cue. No grinding patches were found at the other granite exposures situated near water that we re-inspected.

Analysis

The position of each grinding patch was determined by placing a Global Positioning System receiver (GPS receiver) in the middle. Each patch was measured along its longest axis (length) and orthogonally (width) (Table 1). Depth was not measured, it was too slight: < 1 mm. Three patches could not be measured because the bedrock on which they had formed had subsequently broken, leaving one or other axis incomplete. Individual patches range in size from 150 mm x 100 mm to 750 mm x 600 mm (Table 1). Mean size is about 300 mm x 200 mm; approximating the average size, 310 mm x 160 mm, reported by Grant (1992) for the 487 grinding patches she measured on granite bedrock at Esmeralda Station in northwestern Queensland.

It is probable that patch size relates to the ergonomics of grinding, on which there are no data; so I experimented. A muller can comfortably be pushed about 450 mm away from oneself, when seated cross-legged. Grinding the area immediately in front of one's crossed legs is difficult, however. Hence, the area ground stretches about 300 mm away from the person doing the grinding; the orthogonal dimension may be more variable. I could comfortably cover an area about 400 mm wide. Several of the patches reported on here are much larger than 300 mm x 400 mm, however. All the very large patches are at Boat Hole Rock and Camel Soak. They could be the result of two separate patches merging over time, or be places where two people worked together, although the worn faces are evenly smooth, or they may simply be different from the smaller patches. It is impossible, as yet, to discriminate between these suggestions.

The grinding patches at Boat Hole Rock and Camel Soak might also be bigger than those at Afghan Rock, *Djungari* and Taincrow because water was available more frequently or more reliably at Boat Hole and Camel Soak, allowing greater numbers of people to camp there more often or for longer periods than at the other sites. Boat Hole gnamma is capacious and easy to cover, being long and narrow. It would have been an important source of water to people living in the area in the archaeological past because no other water sources are known within a radius of several kilometres. On the other hand, few artefacts were noted on the colluvium west of the outcrop in which this gnamma has developed; occupation seems to have taken place 200 m to the east at a short stretch of breakaway, where there is a sparse artefact scatter (Gunn & Webb 2006). In contrast, an extensive artefact scatter was found at Camel Soak, suggesting that the site was visited often and/or for long periods and/or by many people. More sites where grinding patches on bedrock are situated close to water would need to be found around Cue before the significance of the pattern just described could be assessed, however.

The grinding areas on 17 grindstones were measured during earlier surveys around Cue (Table 2). In Figure 7 their dimensions are compared with those of the grinding patches on bedrock. This Figure shows that there is no appreciable difference in size between the ground areas on flat and dished grindstones, but that the grinding areas on grindstones are usually smaller than those of bedrock patches.

The grinding area on a grindstone is, obviously, always smaller than the host rock, whose dimensions were probably constrained by weight. Grindstones must be portable. They are usually made of stone not available in the immediate vicinity of where they are found. All the grindstones listed in Table 2 were made from granite. The weight of the largest is estimated to be 29 kg, based on the average density of granite: 2.8. This is about the maximum weight one person can lift and carry easily. The large granite slab hosting grinding patch 1 at Taincrow Rockhole is estimated to weigh about 375 kg and is probably *in situ*. Weight restrictions obviously do not apply to bedrock, hence grinding areas can be bigger, as the very large patches at Boat Hole and Camel Soak demonstrate. Until more grinding patches on bedrock are found in this region, the difference in size between them and the grinding areas on grindstones cannot be explored further.

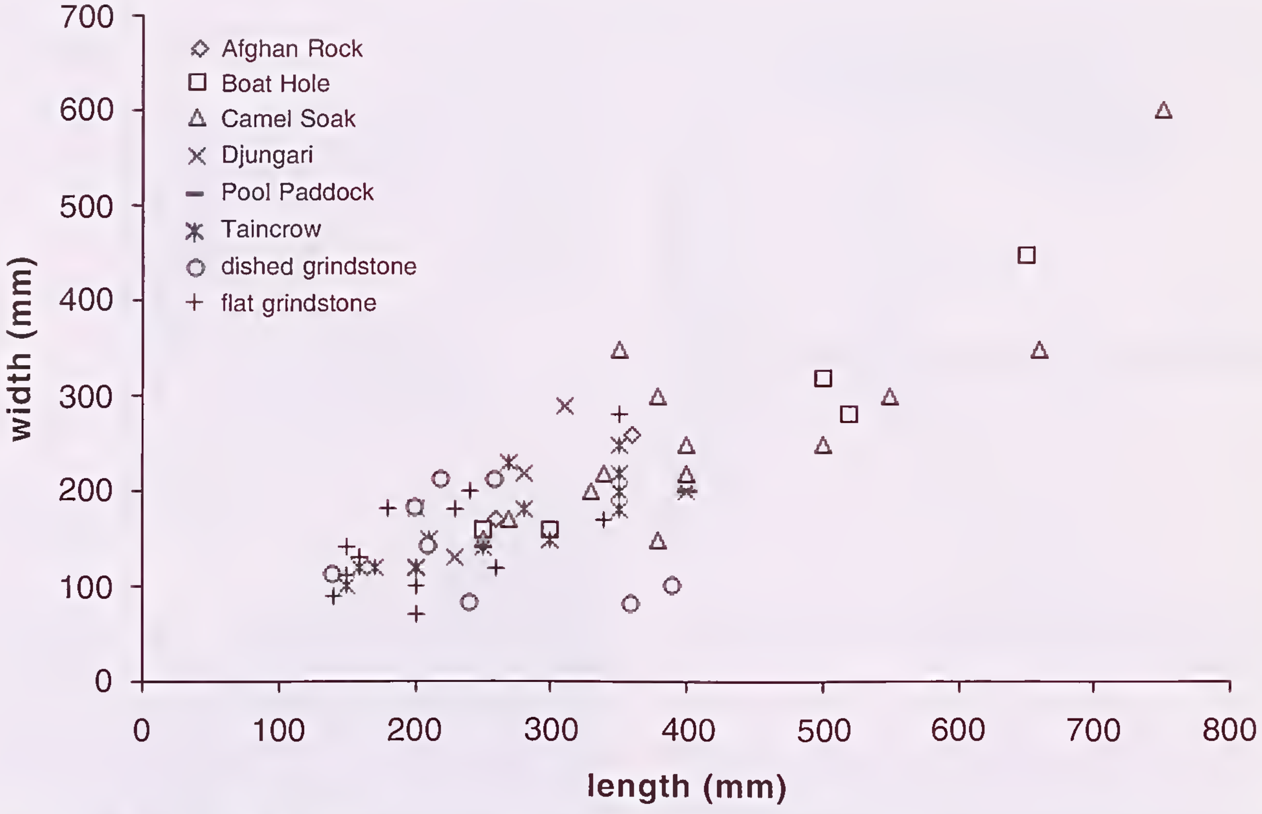

Figure 7. Length and width of grinding patches found around Cue and of the grinding area on some portable grindstones measured by Gunn & Webb (2002, 2003, 2006).

Table 2

Dimensions in millimetres of portable grindstones, and their grinding areas, recorded at sites around Cue (Gunn & Webb 2002:91, 2003:87). The bifacial stone marked by * has a dish ground into the flat grinding area on one side.

type	host L x W x D	grndg L x W x D
unifacial, flat	330 x 260 x 70	150 x 140 x <1
unifacial, flat	400 x 280 x 190	350 x 280 x <1
unifacial, flat	430 x 260 x 90	260 x 120 x <1
unifacial, flat	250 x 140 x 70	200 x 70 x <1
unifacial, flat	250 x 180 x 80	230 x 180 x <1
unifacial, flat	260 x 230 x 75	180 x 180 x <1
unifacial, flat	210 x 150 x 70	160 x 130 x <1
unifacial, flat	420 x 240 x 75	340 x 170 x <1
unifacial, flat	440 x 370 x 50	200 x 100 x <1
unifacial, flat	200 x 200 x 50	140 x 90 x <1
unifacial, well-used	165 x 135 x 60	150 x 110 x <1
unifacial, dished	350 x 210 x 100	200 x 180 x <1
unifacial, dished	330 x 150 x 55	240 x >80 x <1
unifacial, dble dish	510 x 340 x 60	390 x 100 x 40
dish 2		360 x 80 x 20
trimd bifacial, dish	380 x 350 x 70	210 x 140 x 10
'reverse', dished		140 x 110 x 10
bifacial, dished	270 x 220 x 80	260 x 210 x 1.5
'reverse', flat		160 x 130 x <1
*bifacial, flat/dish	340 x 300 x 90	220 x 210 x <1
'reverse', flat		240 x 200 x <1

Discussion

There appears to be a north-south divide within Western Australia in some aspects of Aboriginal culture that is reflected in rock art and the occurrence of grinding patches on bedrock. Almost all the grinding patches on the site register maintained by the Department of Indigenous Affairs (DIA) were found in the northern half of the State: the Pilbara, Kimberley and Great Sandy Desert (Figure 8). While the rock art made in northern and southern Western Australia is also different (Davidson 1952), as discussed further below. This discussion explores the occurrence of grinding patches in relation to geology, the cultural evidence for a north-south divide, the association of grinding patches and rock art, and whether grass seeds were ground on specialised grindstones.

Grinding patches and bedrock geology

The DIA on-line database of site information was searched for sites where grinding had been reported, to provide a context for the sites just described. The database does not, unfortunately, discriminate between axe grinding grooves, grindstones, grinding patches on bedrock and burley holes (depressions in which shellfish were crushed into fish bait). The type of grinding can only be ascertained by studying the file of information on each site. I have only studied the files on the 30 sites where grinding has been reported in the southern half of Western Australia. I have also visited many of those sites during two site verification projects for the South West

Aboriginal Land and Sea Council, funded by Edith Cowan University (Webb & Gunn 2004). The grinding at all those sites is either natural weathering, burley holes or axe sharpening grooves. These features are unlike the bedrock patches reported on here. I have also visited many granite outcrops in the Southwest that house gnammas, lizard traps and rock art (Webb & Gunn 2004). Grinding patches were not found at any of them, despite careful search.

At present, the southernmost site where grinding patches on bedrock have been reported is Kockatea Gully, 5 km northwest of Mullewa (Goode 2002). No details of the grinding patches are given in the site file, however, nor can they be identified in the photograph. This site lies just east of the Darling Fault, which marks the western edge of the Yilgarn Craton. This huge expanse of Late Archaean granite stretches halfway to the South Australian border and from north of Meekatharra almost to the south coast (Myers & Hocking 1988). Were grinding on bedrock dictated by geology, patches could be expected to occur wherever suitable bedrock is emergent; whereas, none are known on the southern half of the Yilgarn Craton.

On the other hand, hundreds of sites with grinding have been reported in the Pilbara. The exact number is unclear because some sites are known to have been recorded (and registered) more than once as different sites. Fewer sites are known in the Kimberley and Western Desert. I have not studied the files on any of these sites, so do not know at how many of them the grinding is bedrock patches, rather than portable grindstones. Nonetheless, the available data suggest that grinding patches on bedrock are a distinctively northern phenomenon. The possible reasons for this will now be explored.

Cultural evidence for a north-south divide in rock art as a guide to understanding the distribution of grinding patches in Western Australia

There is other archaeological evidence for a north-south divide. Davidson (1952) argued that the rock art of Western Australia could be divided into a number of geographical provinces. Stencils predominated in the south and west; line drawings, linear forms, surface painting and solid forms in the Kimberley. 'Emu tracks' were common everywhere except the Kimberley; while geometric designs were not found in the Kimberley or Southwestern Australia. He thought polychrome figures were a feature of northern sites, monochromes typical of southern sites; while linear forms were notably more complex in the Murchison region and most complex in the Kimberley. He said that pictograms and/or petroglyphs of animals and anthropomorphic figures were common in the north and almost absent in the south. He saw the Murchison as a transitional zone where handstencils predominated and petroglyphs were uncommon.

Subsequent research around Cue has revised Davidson's scheme (Gunn *et al.* 1997; Gunn & Webb 2000, 2002, 2003, 2006). Pictograms (chiefly handstencils) are widespread throughout the southern half of Western Australia, although the artwork of the Southwest is more complex than Davidson realised (Webb & Gunn 2004). Petroglyphs (peckings and poundings) are more common around Cue than Davidson thought. Half of all the artwork we have recorded is petroglyphic (Gunn & Webb 2006). Some of the motifs, pecked animal tracks and circles, can clearly be linked to the Panaramitee Tradition which is widely distributed across the Australian arid zone, and reaches its highest expression in the Pilbara (McNickle 1985). Panaramitee petroglyphs have been recorded 125 km northwest of Meekatharra (Stokoe 1959), 150 km southwest of Cue (Franklin 1992) and 70 km northwest of Cue (Gunn & Webb 2003), but are unknown in the Southwest. Gunn & Webb (2002) considered the painted, pecked or pounded animal tracks, geometric elements and linear designs they recorded east of Cue not to be Panaramitee. Instead they attributed them to the Yarraquin Tradition, saying that pounding seemed to have developed from pecking. They concluded that stencilling preceded both those techniques. Stencilling also overlapped with both the Yarraquin Tradition and the large paintings at Walga Rock, 50 km west of Cue, which are related stylistically to Western Desert art (Gunn *et al.* 1997; Gunn & Webb 2000).

This brief summary of the rock art evidence suggests that the area around Cue is linked stylistically to both the Pilbara and the Western Desert and should perhaps be viewed as a southwestward extension of the traditions found in those semi-arid regions. It is also linked to the Southwest by stencilling, which is ubiquitous world-wide.

The area around Cue may also be linked more closely to the Pilbara and Western Desert than to the Southwest by the diet and social customs of its occupants. Grinding on bedrock seems to be related to seed consumption, which played a large part in the diet of Aboriginal people living in arid and semi-arid Australia (Tindale 1977; Smith 1989). Tindale (1974) showed the area where grass seed flour was an important element in Aboriginal diets, his *Panara* culture, spreading across the inland Pilbara as far south as the area around Cue. He said the people of the Murchison region, who now call themselves Yamaji, 'were the southwestern-most people to extensively exploit grass seeds and wet-grind them for the making of forms of bread' (Tindale 1974). The grinding patches on bedrock recently found around Cue support Tindale's contention that the Yamaji ground grass seeds; suggesting they were more closely linked socio-economically to people in the Pilbara than they were to the Noongar to the south. Noongar people did not grind grass seeds; they seem to have relied on tubers as their carbohydrate staple (Grey 1841; Meagher 1974). The Yamaji also ate tubers, of course (Webb 2000).

By the time anthropologists began to study the Yamaji, they were following Western Desert initiation rites, circumcision and subincision, which Tindale (1974) thought spread into the Murchison from the Kimberley or Western Desert, just before the British arrived in Western Australia in the 1820s. These practices separated them from the coastal people to their west and the Noongar to their south whose initiation rites did not include either circumcision or subincision. The division between people who followed those practices and those who did neither appears to have been profound and acrimonious (Gibbs & Veth 2002).

Considered together, this artistic, dietary and cultural evidence suggests that the occupants of the Cue region had closer links with the people to their north and east, than with those to their south and west. Those links become clearer when the places where grinding patches have been found associated with rock art are considered.

Grinding patches and rock art – women's work, men's business?

About 650 sites where grinding is associated with rock art have been reported in Western Australia: 87% in the Pilbara and 11% in the Kimberley (Figure 8). The remaining sites are more widely scattered, although very few have been reported south of 26° S. Not all the registered sites could be plotted on Figure 8 because DIA suppresses the co-ordinates for sites whose files are *closed* for cultural reasons, about 10% of the total known. Nonetheless, Figure 8 is a reasonable representation of the geographic distribution of the sites where rock art has been found in association with grinding; whether that grinding is bedrock patches or portable grindstones is unknown. As noted above, the on-line DIA database does not distinguish between these types of grinding. The distribution pattern seen in Figure 8 does, however, seem to comprise two major regions: the Pilbara and the Kimberley.

In the Pilbara, grinding is associated almost exclusively with petroglyphs. A few sites with both pictograms and

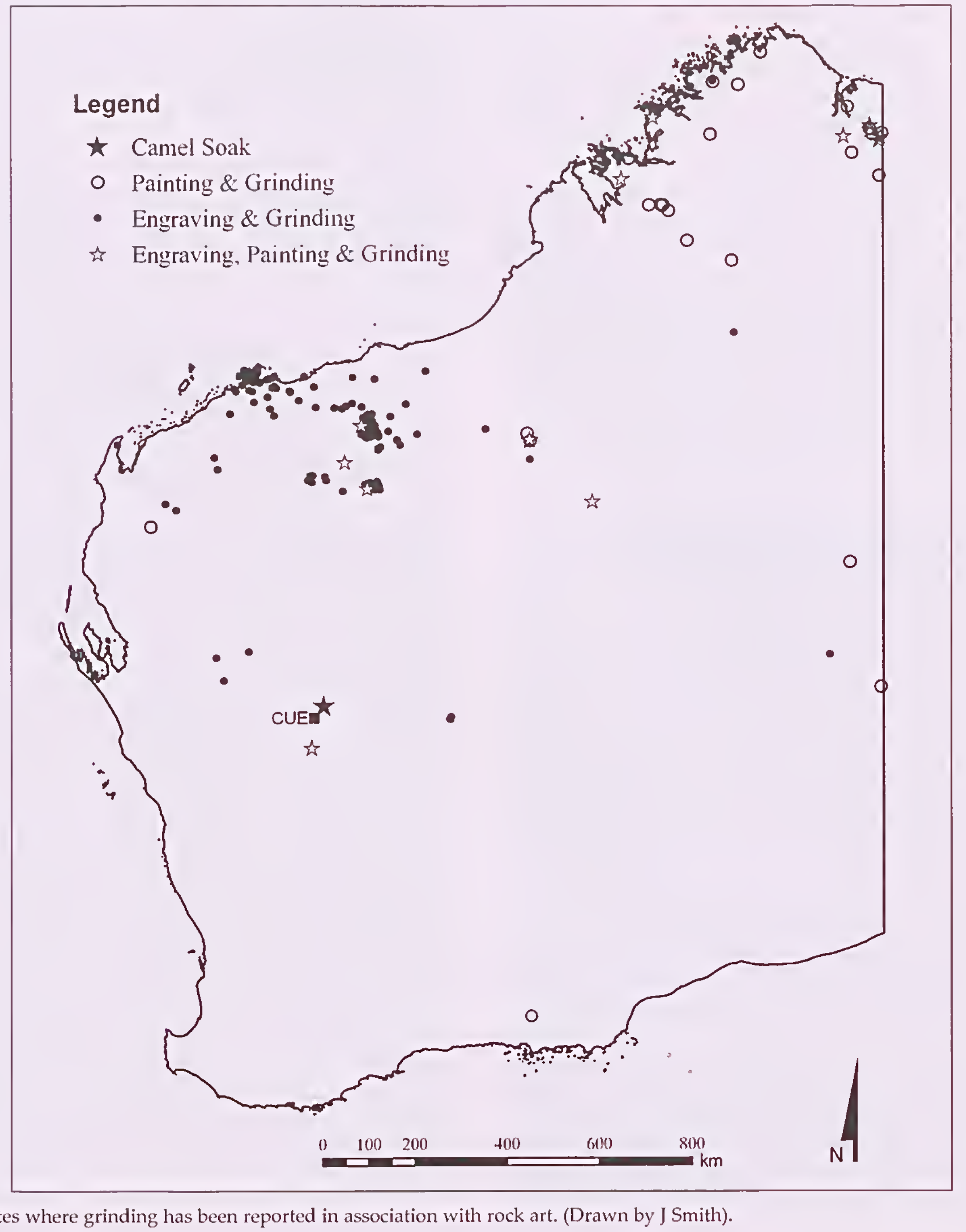

Figure 8. Sites where grinding has been reported in association with rock art. (Drawn by J Smith).

petroglyphs are known, but none with *only* pictograms. In contrast, at half the Kimberley sites, grinding is associated *solely* with pictograms (stencils and/or paintings). Both petroglyphs and pictograms were reported at the other Kimberley sites. If this dichotomy is real, then two sites need to be explained: Mount Ridley, 65 km north of Esperance, and The Granites, 90 km south of Cue. Mount Ridley may be unique. The grinding patch there seems to have been used solely for grinding ochre (Smith 1997). It is located *within* a decorated shelter, whereas patches presumed to have been used for grinding flour are usually found in the open air. The Granites is a major mythological and ceremonial site complex located a few kilometres northeast of Mount Magnet where grinding patches, petroglyphs *and* pictograms have been recorded. This is significant, if the distribution pattern in Figure 8 is real, since it links The Granites to both the Pilbara and the Kimberley, or perhaps to the Western Desert. The file on The Granites is closed, so I do not know whether any of the grinding patches are associated with either petroglyphs or pictograms.

The DIA database lists three rockshelters located about 90 km west of Cue as housing pictograms and grinding. I have examined the information on file about these sites. Two were recorded by DL McCaskill in 1975. He found a number of portable grindstones in one; while at the other grooves had been cut into the rockshelter wall. At the third site, Gunn & Webb (2003:52) noted that a block of saprolite had been abraded on its upper surface; a treatment that seemed to us similar to the ritually rubbed blocks Mountford (1976) reported from the Western Desert. These sites have been omitted from Figure 8 because they do not house bedrock patches.

Figure 4 shows that two of the groups of petroglyphs found at Camel Soak frame grinding patches 1–6. The petroglyphs and patches are patinated to the same degree, suggesting that they were made penecontemporaneously. At many sites in the Pilbara petroglyphs have also been found 'close to or even on top of engravings' (Flood 1990). This juxtapositioning suggests that the relationship of one to the other may have been significant when both were made, raising the issue of who made what (Flood 1990, 1997; Mulvaney and Kamminga 1999). It is generally accepted that grinding flour was 'women's work'. Women probably used most of the portable grindstones and made most of the grinding patches on bedrock, which are considered utilitarian, not to be 'classed as rock art' (Flood 1997). Whereas, men are thought to have made most of the rock art in Australia, particularly at ceremonial sites like Walga Rock (Gunn *et al.* 1997). Not all art was sacred or not to be viewed by women, however. Women clearly made handstencils, for example (Gunn 2006). Whether they made petroglyphs is less certain.

Of course, some grinding patches and petroglyphs could have been made sequentially and diachronically. Flood (1990) said that grinding took place 'on top of' petroglyphs at many places in the Pilbara. In such cases, it is possible that by the time the grinding took place the petroglyphs had lost their significance for the people doing the grinding. Just as, at Walga Rock (Gunn *et al.* 1997), new paintings were made over older paintings, possibly because the older motifs were no longer significant to the people making the new ones.

At present, the juxtaposition of petroglyphs and grinding patches at Camel Soak is locally unique, making the site difficult to interpret. It would appear, however, that if men made the petroglyphs, they also either made the grinding patches, or had no objections to women viewing the motifs; they were public images that could be viewed by anyone. Or, maybe women made *both*? There is little possibility of verifying any of these suggestions, now.

On the other hand, the occurrence at Camel Soak of archaeological evidence more commonly found in the Pilbara supports the suggestion made above that the people living in the area around Cue were more closely linked culturally to the Pilbara than to the Southwest.

Were grass seeds being ground?

Tindale (1974) said the Yamaji 'were the southwestern-most people to extensively exploit grass seeds and wet-grind them for the making of forms of bread'. One of his informants told him that the Yamaji 'had an advantage because they placed great reliance on grass seed food, whereas other people lived only on the hammered seeds of shrubs, did not wet mill grass seed and often went hungry'. Who 'the other people' were is not mentioned. Tindale (1974) also said the Yamaji stored both grass seeds and *'bulibuli' (Tecticornia arborea)* seeds for at least six months in kangaroo skin bags or containers. *T. arborea* is a halophytic chenopod (samphire) found at claypans in the semi-arid zone (Bindon 1996). It is called '*kurumi*' in the Eastern Goldfields (Dix & Lofgren 1974). If the Yamaji wet-milled grass seeds, what sort of grindstones did they use? Gunn & Webb (2002, 2003) recorded 42 grindstones during their surveys around Cue. Of these, 15 are dished; two deeply. One of them is pictured (Figure 9 top). The remainder have flat grinding surfaces (Figure 9 bottom), like the patches described above.

Tindale (1959, 1974, 1977) and Smith (1985, 1988, 1989) argued that wet milling grass seeds led to the development of specialised grindstones with deep grooves, that contrasted markedly with 'amorphous' grindstones with flat grinding surfaces that were used for a variety of other tasks. My experiments suggested that pounding (of hard *Acacia* seeds) can be carried out more easily on a flat grindstone, whereas rubbing tends to create grooves, but whether a specialised grindstone was *necessary* to process grass seeds is open to question. From their analysis of grinding material, Davidson & McCarthy (1957) concluded that it was difficult to classify grindstones into discrete types because shape seemed to reflect degree of usage. Gorecki *et al.* (1997) concurred; arguing that, rather than being discrete types, amorphous and double-groove grindstones probably represent opposing ends of a continuous sequence of grindstone development. One of the portable grindstones Gunn & Webb (2002) recorded seems to support that contention. It had a shallow groove ground through a previously flattened face (Figure 9 bottom), suggesting that the way it was used changed over time. Gorecki *et al.* (1997) argued that a really deeply-grooved grindstone, like the one in Figure 9 (top) where the deeper groove is 40 mm deep, would be difficult to use. They suggested that such grindstones were actually discards, not specialised artefacts for wet milling grass seeds. It might

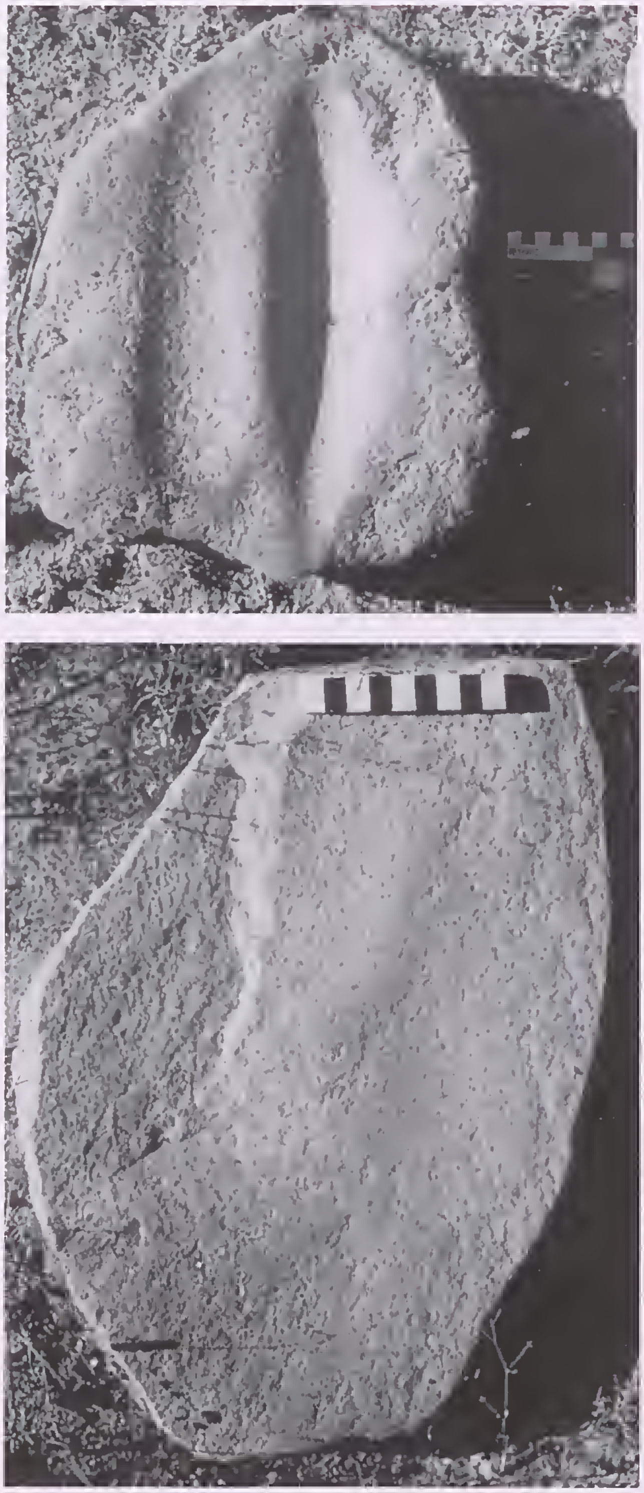

Figure 9. Two grindstones (photos RG Gunn): one with two grooves, one much deeper than the other, the other flat with a secondary dish.

be argued that the deeper groove in Figure 9 (top) had been abandoned for the shallower one, which is 20 mm deep.

Gorecki & Grant (1994) noted that some of the bedrock patches they recorded in northwestern Queensland had striae and carried traces of silica gloss, compatible with grass seed processing. If the people living around Cue were grinding grass seeds, silica gloss might have been found on the patches described here. Keeley (1980) showed that gloss visible to the naked eye develops very rapidly and is durable. It is also unmistakable. I did not see it on any of the bedrock patches found around Cue. These patches were all quite hard to see, except under oblique lighting, being mainly detected by touch. Lantzke (1990) did not mention finding striae or silica gloss on any of the grindstones he studied from around Shark Bay, either. While gloss was not the focus of his research, had it been present, he could hardly have failed to notice it and ought to have mentioned it.

Gorecki & Grant (1994) suggested that the need to transfer the paste produced by wet milling into a container where it could be moulded into damper restricts the shape and location of grinding patches on bedrock: some sort of lip is required at one end of the patch to enable the grinder to scoop up the paste. None of the patches described above have such features; they are simply smoothed areas, sometimes barely distinguishable from the surrounding bedrock. If Gorecki & Grant (1994) are correct, the patches reported on here were probably *not* used for wet milling grass seeds, but for the other tasks for which grindstones are known to have been used (Gould 1969, 1980; Yohe *et al.* 1991; Balme *et al.* 2001): pounding hard seeds, pulverising small animals or grinding ochre.

Conclusion

The grinding patches on bedrock discussed above seem to document a southward extension of an aspect of Aboriginal life that is well-documented in the Pilbara and further north. This link between the area around Cue and the Pilbara is paralleled by some other types of evidence, especially rock art and the presence at one site of petroglyphs flanking the grinding patches. It is concluded that the people living around Cue were more closely linked culturally to those occupying inland northern Australia than they were to those living on the Indian Ocean coast or in the Southwest.

Acknowledgements: R.G. (ben) Gunn drew the original site plans and took the photographs during fieldwork we undertook jointly between 1999 and 2004 with funds provided by the Australian Institute of Aboriginal and Torres Strait Islander Studies in Canberra (grant nos. 6175, 6542, 6544 and 6804) to Thoo Thoo Warninha Aboriginal Corporation in Cue. Both organisations are thanked for their support of our research. Ben is not responsible for the arguments advanced above, however. Alana Rossi redrew most of the figures. Jodee Smith drew Figure 8 from data supplied by Tanya Butler (Department of Indigenous Affairs). The final version of this paper benefitted greatly from critical comments made on earlier drafts by Caroline Bird, Sylvia Hallam and two anonymous referees.

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Journal of the Royal Society of Western Australia, 90: 127–136, 2007

Seasonal and spatial variation in *Salmonella* infections rates in quokkas (*Setonix brachyurus*) on Rottnest Island, Western Australia, in areas of human contact

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Manuscript received October 2006; accepted June 2007

Abstract

A sampling programme to determine the seasonal incidence of *Salmonella* infections in the marsupial quokka, *Setonix brachyurus*, on Rottnest Island, was carried out in public contact areas over the period March 1984 to March 1985. The study followed an unusual rise in the frequency of *Salmonella adelaide* infections in quokkas foraging in the Thompson Bay settlement area and isolations from catchment waters and sewage effluent. A total of 670 tagged quokkas was swabbed in the island's three settlement areas, plus Kingston Barracks, Garden Lake and Lighthouse swamp. A total of 1,139 duplicate swab samples was collected from quokkas and 713 swabs from 244 animals recaptured more than once. Twenty five *Salmonella* serotypes were identified, including *Salmonella javiana* and *S. typhimurium* Phage Type 202 associated with human cases previously traced to the island. Significant differences were found in rates of infection in quokkas and these peaked at approximately 40% in the resident population at Lighthouse swamp, and at 30% in settlement areas during the summer months. Based on population estimates, a minimum of 200 infected animals are likely to frequent the Thompson Bay settlement area during the peak summer vacation period. Infection rates fell below 5% in settlement areas during the winter period but remained around 20% in the Lighthouse Swamp population. The majority of *Salmonella* infections in recaptured animals was classified as transient and few quokkas showed evidence of a carrier state, or absence of infection throughout the sampling period. *Salmonella* infections were higher in juvenile quokkas than adults in settlement areas and in adult females at Lighthouse Swamp. The large population density of quokkas foraging nocturnally for food in settlement areas maintained high levels of ground contamination with infected droppings. However, evidence of progress in long-term management strategies to promote natural behaviour in the island's wildlife and ameliorate public health problems is consistent with the absence of cases of salmonellosis traced to the island during the monitoring period and in subsequent years marked by significant increases in visitors to the island.

Keywords: Salmonellosis, zoonoses, Rottnest Island, marsupial, public health

Introduction

Salmonella isolations from wild animals in different countries was reviewed in a report on serotypes identified by the Salmonella Reference Laboratory in the United Kingdom by (Taylor 1969) and recently updated (Anon. 2006). The possibility of infections caused by wildlife spilling over to humans has been highlighted in a recent review, (Kruse Kirkemo & Handeland 2004) following on early studies in Panama (Kourany Bowdre & Herrer 1974), Trinidad (Everard Tota Bassett & Ali 1979), and India (Kaura & Singh 1968; Sambyal & Sharma 1972). In Australia, *Salmonella* infections acquired from wildlife are known to persist in non-urban aboriginal communities (Iveson 1983; Iveson Mackay-Scollay & Bamford 1969). The surprise discovery in 1972 of a major reservoir of *Salmonella* infection in the small marsupial wallaby *Setonix brachyurus*, known as the quokka, on Rottnest Island and the tracing of infections in humans to droppings from infected animals and contamination of wells and water storage tanks (Iveson & Bradshaw 1973), alerted public health authorities to the need for improved preventative measures on this small island resort in Western Australia. The findings also raised questions concerning the management of *Salmonella* infections in wildlife populations on the island, which were first addressed in a Public Health report and management

plan prepared for the then Rottnest Island Board (Iveson & Bradshaw 1978).

Over the subsequent period 1972–2000, a total of 31 laboratory-confirmed cases of human salmonellosis were diagnosed in residents and visitors to the island involving 9 *Salmonella* serotypes. These comprised *S. javiana* 16, *S. typhimurium* 6, *S. muenchen* 5, *S. saintpaul* 3, *S. chester* 1, *S. oranienburg*, *S. wandsbeck* 1, *S. waycross* 1, and *S. IIIb diarizonae*. *Salmonella javiana* has caused severe gastro-enteritis in infants exposed to quokka droppings and hospitalisation has been needed to treat the infection. Two patients were infected with multiple serotypes. *Salmonella javiana* and *S. typhimurium* Phage Type 202 have been the major strains implicated in human infections and non-human isolations on Rottnest Island have been recorded from quokkas, horses, seagulls, swallows, reptiles, water supplies and sewage (Iveson & Hart 1983). The finding of *S. javiana* infections in quokkas, horses, humans and well waters at the Riding School, resulted in its closure and the removal of horses from the Island. The undoubted virulence of *S. javiana* and its absence from the food chains of humans and livestock on the mainland also resulted in a test programme and quarantine measures to exclude infected quokkas being translocated to mainland fauna reserves (Short Bradshaw Giles Prince & Wilson 1992).

This unusual pattern of exposure in humans to reservoirs of infection in wildlife on the island differs from the usual pattern of food-borne infections that is commonly seen in urban areas on the mainland. *Salmonella javiana* and *S. typhimurium* PT 202 are rarely isolated from humans resident in mainland Australia and have not previously been detected in domesticated animals or in indigenous fauna. A total of 10 serovars classed as exotic isolates introduced by humans and domestic animals has been discovered in the period 1972 to 2000 on Rottnest Island and comprise *S. agona*, *S. bovismorbificans*, *S. derby*, *S. havana*, *S. infantis*, *S. javiana*, *S. livingstone*, *S. meleagridis*, *S. newport* and *S. typhimurium*. The majority of these serovars has been recorded from quokkas in settlement areas and all of the serotypes were also isolated from sewage effluent, suggesting latent infections in humans either resident or visiting the island.

Although monitoring of sewage effluent provides evidence of silent carrier infections in humans on the island, symptoms of gastroenteritis in residents, visitors and, occasionally, research workers on the island have rarely been matched by collection and examination of patient specimens. Surprisingly, the 31 cases of salmonellosis and 35 isolations recorded from humans on the island were derived from only 52 faecal samples and the majority of cases was diagnosed prior to the upgrading of public facilities on the island, as recommended in the Rottnest Island Management Plan and reviewed by (Portlock 1991). Collective studies of *Salmonella* infections in settlement areas on Rottnest Island commenced in 1972 and revealed infection rates in quokkas ranging from 20–30%. Specific information on the gain and loss of serotype infections was lacking, however, and following the discovery of 20 (74%) *S. Adelaide* infections in quokkas in the main settlement area on the Island this suggested a possible epizootic in quokkas.

In view of the risks to public health, data were obviously needed on the seasonal incidence of *Salmonella* infections in quokkas inhabiting settlement areas and other contact areas on the Island. The aims of the study were thus:

to monitor infection rates in individually-tagged quokkas frequenting the settlement areas on Rottnest Island over a 12-month period, and to compare these with infection rates of quokkas resident in other parts of the Island.

To assess the health threat to tourists visiting the Island of the practice of hand-feeding quokkas at the bus stop adjacent to Lighthouse swamp.

Materials and methods

The Thompson Bay settlement and associated camping area on Rottnest Island (31°60'S, 115°30'E) occupies an area of approximately 2 km^2 and is bordered by the water-catchment area, sewage facility, golf course and Garden Lake (see Figure 1). Remnants of native vegetation provide daytime habitat for quokkas that are attracted to feeding sites in the early evening (Kitchener 1972). Distances between sampling locations ranged from 100–500 m and were subject to a degree of overlap during capture and recapture over the year.

Quokkas were caught with hand-held nets between 1800–0200 hours in the settlement and Kingston Barracks/Bickley Swamp area, and between 1100–1600 hours at the tourist feeding site, close to Lighthouse Swamp. Animals were ear-tagged individually, scored as adults or juveniles, sexed and duplicate rectal swabs were placed in 5 mL of strontium chloride B enrichment broth (Iveson 1971) and isolation procedures for serotypes are detailed in Hart Iveson Bradshaw & Speed (1982). Average times for the tourist and vacation feeding activities averaged from 15 min to 45 min on 1–4 daily visits during the peak summer period and involved hand-feeding in roadside areas littered with many droppings. A number of animals was also sampled at the alternate Longreach and Geordie Bay settlements, located on the north coast, approximately 2.5 km from the main settlement area in Thompson Bay. Samples were collected on 10 occasions over a 12-month period from March 2, 1984 to March 8, 1985. The sampling effort was deliberately concentrated over the summer months when public numbers were greatest and the infection rate in quokkas was expected to be at its highest. Capture and recapture of tagged quokkas allowed approximate estimates of local populations to be calculated, using a simple Lincoln Index, as modified by Bailey (Bailey 1952; Lincoln 1930). Most individuals were recaptured less than 100 m from the site of their original capture, but a small number of individuals was highly mobile and any quokkas that were recaptured more than 500 m from their initial capture site were classified as 'mobiles' are analysed separately.

Data on *Salmonella* infections were analysed statistically using ANOVA and Chi-squared tests with Yate's correction.

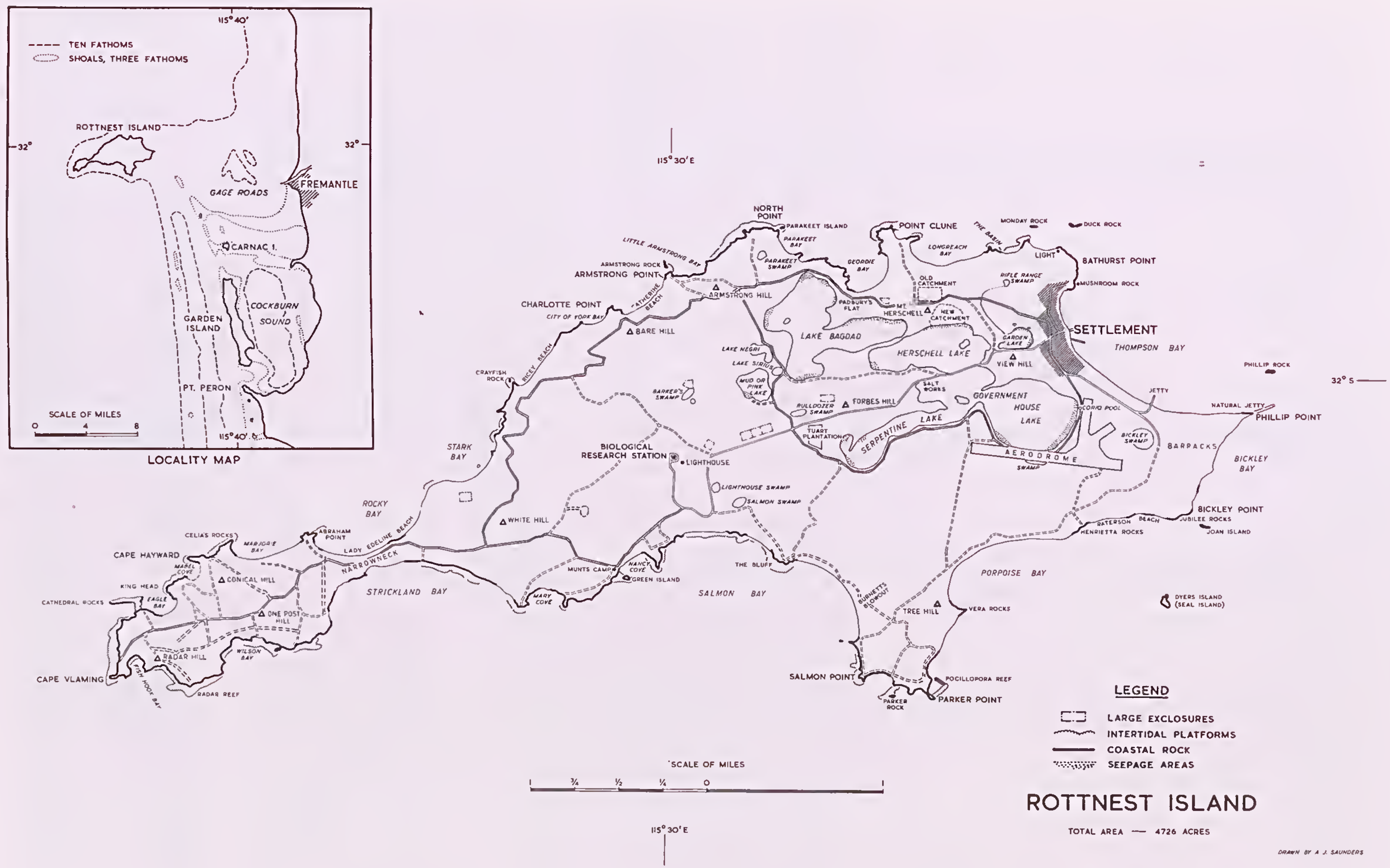

Figure 1. Map of Rottnest Island located 20km off the coast of Perth in Western Australia, showing salt lakes, the main Thompson Bay Settlement area, and other collecting sites at Kingston Barracks, Bickley Swamp, Garden Lake and Lighthouse Swamp.

Table 1

Results of a 12-month *Salmonella* recapture programme of quokkas, *Setonix brachyurus,* on Rottnest Island carried out in areas of public contact between 1984 and 1985.

Quokkas	Settlement Areas	Camping Area	Kingston/ Bickley	Lighthouse Swamp	Mobiles	Totals
No. Tagged	344	91	86	100	49	670
Males	158	62	38	43	30	331
Females	186	29	48	57	19	339
No. Positive (%)	71 (20.6)	23 (25.3)	36 (41.9)	67 (67)	10 (20.4)	207 (30.9)
Recaptures	69	25	27	75	49	284
No. Swabbed once (1)	276	66	59	25	0	426
Twice (2)	56	20	22	15	26	139
(3)	10	5	3	25	14	57
(4)	2		2	7	3	14
(5)				9	5	14
(6)				8	1	9
(7)				4		4
(8)				7		7
Total swabs	426	121	120	335	137	1139
Total Serotypes	20	8	15	14	6	25 (25)
Total Isolations	81	27	54	133	14	309
Juveniles	23	4	8	29	3	58

Results

A total of 670 quokkas was tagged at the 4 major sites comprising settlement and camping area, 435; Kingston/ Bickley Swamp, 86; Lighthouse Swamp, 100; 'mobiles', 49. *Salmonella* isolation rates over the one-year period, including recaptured animals, averaged 21% in the settlement area, 42% in Kingston and Bickley Swamp and 67% in Lighthouse swamp, with a marked seasonal pattern, decreasing over the southern winter period. A combined total of 197 (32%) animals yielded *Salmonellae* at the four locations and 25 serotypes were identified from a total of 1002 swab samples (excluding mobiles) as shown in Table 1. A small number of faeces voided during collection of swab samples from adults and pouch young yielded an MPN (Most Probable Number) ranging from 10–1000 *Salmonella* organisms per gram. The efficiency of swab procedures in isolating *Salmonella* serotypes *versus* faecal samples for *Salmonella* isolations was 67% (Hart *et al.* 1982).

The major serotypes isolated from quokkas in the Settlement areas and the camping area were *Salmonella typhimurium* PT 202 (21), *S. muenchen* 17, *S. adelaide* 13, *S. javiana* 12 and *S. wandsbek* 11, with similar results recorded at Kingston Barracks. At Lighthouse swamp *Salmonella adelaide, S. chester, S. orientalis and S. wandsbek* were the major serotypes isolated. *Salmonella*

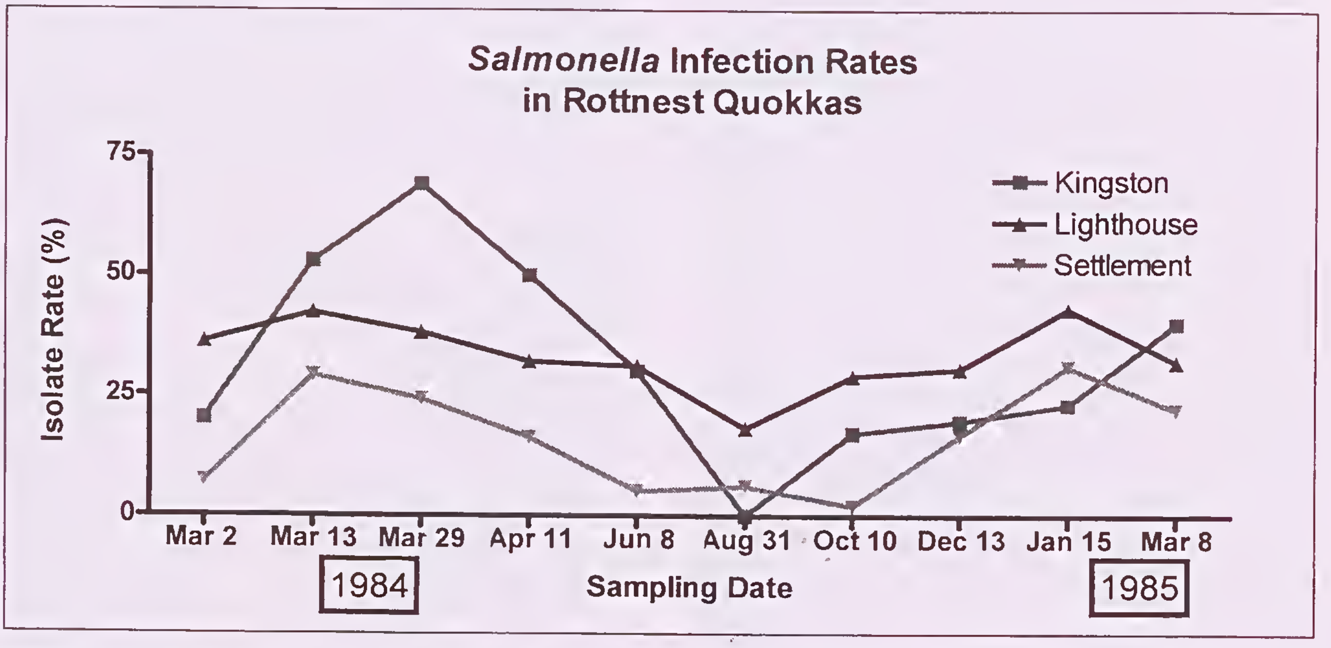

Figure 2. Seasonal variation in *Salmonella* percentage infection rates in quokkas (*Setonix brachyurus*) on Rottnest Island over a 12-month period from March 1984 to March 1985. Sampling locations shown are Kingston Army Barracks and Bickley swamp (Kingston), Lighthouse Swamp (Lighthouse), Garden Lake and the main Settlement area in Thompson Bay (Settlement).

Table 2

Salmonella isolations by serovars from tagged quokkas (*Setonix brachyurus*) in close associations with humans on Rottnest Island over a 12-month period from 1984-1985.

Salmonella serotypes	Settlements	Camping Area	Kingston Barracks	Lighthouse Swamp	Mobiles	Totals
adelaide	10	3	5	23	3	44
II alsterdorf			1			1
anatum	3	1	2			6
birkenhead	2			2		4
bootle	4					4
bovismorbificans	2					2
chester	1	1		16		18
decatur	3	1	1	2	1	8
infantis	1			1		2
javiana	8	4	8	1	2	23
muenchen	12	5	5	13	3	38
newington	2			6		8
oranienburg				8		8
orientalis	4		3	14	1	22
orion	3		1			4
potsdam	2					2
rottnest	1		1	7		9
typhimurium	11	10	10		4	35
II wandsbek	9	2	8	36		55
IV waycross	2		4			6
53:d:z_{42}	1		1			2
IIIb 25:l v:z_{53}	3		1			1
IIIb 50:K:z_{35}				1		1
IIIb 61 l v:z_{35}				3		3
IIIb 61:$z_{52}z_{53}$	2		3			5
Total Isolations	81	27	54	133	14	309
Total Serotypes	20	8	15	14	6	(25)
Quokkas tagged	344	91	86	100	49	670

javiana was isolated once but *S. typhimurium* remained undetected. A summary of the serotypes isolated at all sites in contact with the public, including isolations from mobile quokkas, is given in Table 2.

Differences in infection rates between areas

Examination of all field data reveals three major groupings based on the infection rates in the 670 quokkas examined. These are Kingston Barracks, Lighthouse Swamp and the settlement areas and variation over time in infection rates at these sites is graphed in Figure 2. A marked seasonal pattern is evident in all 3 sites, with infection rates falling to between 0 and 20% in winter and reaching a peak in late summer/autumn. A one-way ANOVA shows significant variation between the infection rates in the 3 sites with $F_{2,27} = 4.813$ and $P = 0.0163$. Bonferoni's *posteriori* Multiple Comparison Test shows that infection rates in the Settlement areas are significantly lower than both Kingston Barracks and Lighthouse Swamp with $P < 0.05$.

Differences in infection rates based on age and sex

The number of juveniles sampled was generally too small for statistical analysis except in the case of the settlement areas where the infection rate in juveniles was significantly higher than in adults ($X^2 = 5.06$, $P = 0.02$, see Table 3). A sex difference was only found in adults from the Lighthouse Swamp sample where a higher infection rate was seen in females ($X^2 = 4.349$ $P = 0.037$) as shown in Table 4. This difference was not due to a seasonal bias in sampling of the two sexes as a total of 67 quokkas was positive at least once of which 30 were males and 37 females.

Changes in infection rates in individual quokkas

Only at Lighthouse Swamp were individuals recaptured frequently and thus was it possible to observe changes in infection status in a single animal over both the short and long term. Data from 19 quokkas that were

Table 3

Comparison of *Salmonella* infection rates in adult and juvenile quokkas, *Setonix brachyurus*, from settlement areas on Rottnest Island, with percentages in parentheses

Quokkas	Positive (%)	Negative (%)	Totals
Adults	101 (15.4)	555 (84.6)	656
Juveniles	15 (28.3)	38 (71.7)	53
Totals	115 (16.2)	594 (83.8)	709

Table 4

Comparison of *Salmonella* infection rates in male and female adult quokkas, *Setonix brachyurus*, from Lighthouse Swamp on Rottnest Island, with percentages in parentheses

Quokkas	Positive (%)	Negative (%)	Totals
Males	36 (27.5)	95 (72.5)	131
Females	63 (39.9)	95 (60.1)	158
Totals	99 (34.3)	190 (65.7)	289

Table 5

Salmonella infection records for individual quokkas over a 12-month period of sampling at Lighthouse Swamp on Rottnest Island.

Quokka	March 2 1984	March 13 1984	March 29 1984	April 11 1984	June 8 1984	August 31 1984	October 10 1984	December 13 1984	January 15 1985	March 8 1985	No. Times Sampled
102 ♂	-ve	-ve	-ve	-ve	-ve	-ve	-ve				7
103 ♂	-ve	-ve	-ve	-ve	*berkenhead*	-ve			-ve	-ve	
107 ♀	-ve		*orientalis*	-ve	-ve		-ve	-ve	-ve	*wandsbek*	8
109 ♂	-ve		-ve	-ve				-ve	-ve	*muenchen*	6
176 ♂	-ve			-ve	-ve		-ve	-ve	-ve		6
179 ♂	-ve	-ve	-ve	-ve				-ve	-ve	-ve	7
180 ♂	*adelaide, orientalis*		-ve	*orientalis*			-ve		*orientalis*	-ve	6
183 ♂	*rottnest*	*rottnest*	*rottnest*	-ve	-ve	-ve	-ve	-ve			8
196 ♀		-ve	*wandsbek*	-ve	*oranienburg*			*chester*	*chester*	*javiana decatur*	7
198 ♂		*chester*	*chester*	*chester*	-ve	-ve		*chester*	*wandsbek*	-ve	8
203 ♀		*muenchen wandsbek*		-ve 6	*muenchen*	-ve	*adelaide,*				
284 ♂		-ve	-ve	*newington*	-ve		-ve	-ve	*rottnest*	*wandsbek*	8
288 ♂		-ve	*muenchen adelaide*	*orientalis*	-ve			-ve		-ve	6
292 ♀		-ve	-ve	-ve			-ve	-ve	*adelaide*	*wandsbek*	7
303 ♀			*adelaide*	*adelaide*	-ve	-ve	*wandsbek*	-ve			6
308 ♀			-ve	-ve		-ve	-ve	*wandsbek*		-ve	6
310 ♂			-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve	8
311 ♂			-ve	-ve	-ve	*wandsbek, adelaide*					
389 ♂			-ve	*oranienburg*	*oranienburg*	*oranienburg*		*oranienburg*	*oranienburg*		6
No.+ve	2/8	3/10	6/17	6/19	4/14	2/10	2/12	5/15	7/14	5/13	42/132

caught and sampled a minimum of 6 times are presented in Table 5. Infections were predominantly transient, involving 10 different serotypes. Only 2 quokkas (male 198) infected with *S. chester* and (male 389) infected with *S. oranienberg* showed evidence of infections exceeding a period of 6 months. Conversely, 9 animals showed evidence of being free from infection for several months. It is possible, however, that when low numbers of organisms are present per gram of faeces, i.e. < 10, the standard swabbing procedure may fail to detect *Salmonella* (Hart *et al.* 1982).

In the Thompson Bay settlement areas, including the camping area, Longreach Bay and Geordie Bay, 435 individual quokkas were captured and 93 of these recaptured one or more times. Ninety five of these recaptures were within a 30-day period and could be subjected to analysis. Fifteen of these were positive initially and 14 on the second occasion. In the first group of 15, 8 were subsequently negative, 4 were positive with a different serotype and 3 (20%) were positive with the same serotype. Seven quokkas were negative at the first sampling but showed as positives during sampling in the following months. Of all the 93 animals recaptured in the settlement areas, only 4 were ever positive with the same serotype twice.

In the Lighthouse Swamp population there were 100 individual quokkas tagged and swabbed with a total of 310 swabs from 75 recaptures. Of the 62 quokkas found to be positive at the first sampling time, 38 were subsequently negative, 7 were positive with a different serotype and 17 (27%) were positive with the same serotypes.

In the Kingston Barracks/Bickley Swamp sample there was a total of 86 individuals tagged and 27 recaptures (second sampling) and 13 more recaptures at subsequent times. Of the 8 quokkas that were positive on the first sampling, one was negative subsequently, 4 were positive with a different serotype and 3 (38%) were positive with the same serotype.

Movement of Animals

There was movement of quokkas between Kingston Barracks, Bickley Swamp and the Settlement. These individuals, and any others moving more than 500 m, were scored as 'mobiles' on reaching the settlement. There were frequent movements by quokkas of over 50 m between sampling sites within the settlement but the majority of animals was captured only on few occasions in the camping area, as well as in the main settlement area. Within the settlement and Kingston Barrack/Bickley Swamp sites, 114 individuals were recaptured only at the same site as their initial capture, showing evidence of high philopatry, whilst 48 individuals were recaptured in at least one other site. There was great variation in the length and frequency of movements recorded in the mobile groups with some individuals being recaptured in other sites and then reappearing at the initial site of capture. Only a few quokkas, however, were captured at more than two sites, even when adjacent or nearby.

The frequency of movements and approximate distances travelled by quokkas are presented in Table 6 with 50% of these under 100 m, highlighting the basically sedentary nature of the quokka. Only 14% of the records were in excess of 500 m, five being recorded at 2100 m between Kingston Barracks and the camping area.

Table 6

Frequency of movement and distances travelled by tagged quokkas, *Setonix brachyurus*, on Rottnest Island.

Distance Travelled	Number	Frequency (%)
<100 m	29	50
100-200 m	12	20.5
200-500 m	9	15.5
>500 m 'Mobiles'	8	14
Totals	58	100%

Table 7

Estimates of population size at various capture sites for the quokka, *Setonix brachyurus*, on Rottnest Island. For the location of sites, refer to the text.

Capture Site	Population Estimate
Camping Ground and Lodge	360
Garden Lake	175
Police Station	64
South Settlement	75
Lighthouse Swamp	98
Kingston Barracks and Bickley Swamp	101
Total	873

Population Estimates

Very approximate estimates of population size for the various capture sites, based on mark-and-recapture efforts, are summarised in Table 7. The main settlement area at Thompson Bay, comprising Bathurst Point, the camping ground, Lodge, Garden Lake, Police Station and South Settlement supports an estimated population of 674 quokkas which translates to an extraordinarily high density of approximately 21 $animal.ha^{-1}$. The Lighthouse Swamp site suggests that a discrete population of approximately 100 individuals is receiving supplementary feeding from tourists. The Kingston Barracks/Bickley Swamp population is roughly of the same size but quokkas are not fed by tourists.

Human Transmission and Public Health Issues

During the study period, patients exhibiting symptoms of gastro-enteritis rarely submitted faecal samples and *S. typhimurium* PT 202 was isolated from one patient. Monitoring of the sewage system revealed 26 serotypes and *S. Adelaide, S. chester, S. javiana, S. muenchen* and *S. typhimurium* PT 202 were detected in coastal waters, catchment sumps and water storage tanks. One hundred and twenty samples of seagull droppings collected from *al fresco* dining areas popular with the public were tested and resulted in the isolation of 11 serotypes including *S. adelaide, S. javiana* and *S. typhimurium* PT 202.

Discussion

Salmonella in wildlife

There is an increasing appreciation of the widespread occurrence of *Salmonella* serovars in wildlife species, and

of the possibility of zoonotic infections (Kruse *et al.* 2004) with Taylor Latham & Woolhouse (2001) estimating that of 1,415 known human pathogens, 62% are of zoonotic origin. An early paper by Bool & Kampelmacher (1958) reported that wild animals were carriers of *Salmonella* and Kourany Myers & Schneider (1970) identified amphibians and reptiles as common carriers. Everard *et al.* (1979) isolated 20 serovars of *Salmonella* from 44 out of 219 animals in Trinidad and Grenada with the toad, *Bufo marinus*, being the most frequently infected. Evidence of transmission of *Salmonella typhimurium* O: 4–12 from wild passerine birds from to humans was reported in Norway in 1998 (Kapperud Stenwig & Lassen 1998). A total of 33 *Salmonella* serovars was isolated from 34 symptom-less reptilian species in Indiana County, Pennsylvania, adding support to the contention that *Salmonella* is a natural member of the intestinal flora of herpetofauna (Chambers & Hulse 2006; Minette 1984). Fifty nine different serotypes of *Salmonella* were isolated from 25 species of wildlife, including crocodiles, in Queensland over a 20-year period but the major serotype infecting humans in north Queensland was absent from the reptiles (Thomas Forbes-Faulkner Speare & Murray 2001). Recent publications have documented the occurrence of *Salmonella* infections in moose (*Alces alces*) in Norway (Aschfalk Hundertmark Bendiksen Arnemo & Elchen 2003), the New Zealand endangered passerine bird, the Hihi (*Notiomystis cincta*) (Ewen Thorogood Nicol Armstrong & Alley 2007) and a wide range of wildlife species in the Nairobi National Park (Gitter & Brand 2005).

Salmonella in the quokka

The first isolation of a *Salmonella* serovar from the quokka was in 1972 (Iveson & Bradshaw 1973) and the fact that it was a rare south-east Asian serotype (*S. javiana*), unknown on the mainland of Australia, prompted the initial investigations of its ecology on Rottnest Island Hart Iveson & Bradshaw 1987; Iveson & Bradshaw 1978). The differences between infection rates found in the present study are consistent with the results of general area comparisons by Hart Bradshaw & Iveson (1985); and Iveson & Bradshaw (1973). This early work established that quokkas in the settlement area were in the best physical condition of animals on the island and exhibited the lowest rates of infection of approximately 20% in all seasons compared with rates of 40–70% from other sites. Thus, paradoxically, infection rates are lowest in areas of greatest human contact, but this would appear to be due to the supplementary feeding that the quokkas receive from tourists in the settlement and the tourist site at Lighthouse Swamp, which helps to maintain their body condition during the adverse summer period, and resistance to infection. Hart *et al.* (1987) similarly established that quokkas collected at the Island rubbish disposal site had low infection rates year round and high physical condition, measured with a meristic condition index relating body mass to bone length (Bakker & Main 1980).

Variation in infection rates

Over most of the island, away from settlement and recreation areas, there is a dramatic change in the infection rate, which cycles seasonally, approaching 70% in summer and falling to 0–30% in winter. Hart (1980) found that Bickley Swamp, which is near the Kingston Barracks, was intermediate. Lighthouse Swamp is also intermediate, reflecting probably the impact of daily feeding by tourists on the condition of the quokkas at this site. The lower results for the late summer of 1985 included in the analyses are considered atypical because of unseasonable rains that fell on the island in the summer of 1984–85. No evidence of the marked rise in infections and epizootic of *S. adelaide* recorded earlier in the settlement area and at Lighthouse Swamp was found in subsequent studies and *S. adelaide* infections declined in incidence to previous levels. *Salmonella javiana* was isolated on 21 occasions in the combined settlement, Kingston Barracks and campsite area, but only once at Lighthouse Swamp. A similar pattern of isolations occurred with *S. typhimurium*. The vast majority of these strains were Phage Type 202 in quokkas inhabiting settlement areas, the camping area and Kingston Barracks. Analysis of infection rates in males, females and juvenile quokkas showed that only at one site, Lighthouse Swamp, was there any evidence of discrimination on the basis of sex and it was concluded that Public Health procedures should not focus on any particular age group or sex when collecting samples.

Recapture rates

Analysis of the fate of infections in recaptured animals revealed that infection rates conformed to the seasonal pattern and was estimated at 20% for the settlement, 28% for Lighthouse Swamp and 38% for the Kingston/Bickley Swamp population. These estimates are fairly consistent, despite differences in infection rates between the study areas. All of the *Salmonella* isolations and re-isolations recorded for comparative purposes were made in summer and the majority were within a two-week period following the primary isolation. The possible bias involving failure to detect small numbers of organisms and subordinate strains in mixed infections by the swab procedure has been investigated by Hart *et al.* (1982) and applying the minimum level of recovery it is estimated that only 50% of serotypes detected are still present after 2 weeks. The numbers of organisms excreted are thus below the dosage likely to pose a significant hazard to humans, assuming contamination of foodstuffs, water supplies and coastal waters is avoided.

There is some evidence that serotypes do persist in carrier animals over long periods of time. Quokkas No. 198 with *S. chester* and No. 389 with *S. oranienberg* at Lighthouse Swamp, for example, each retained a given serotype for 9 months. Evidence that these infections represent a carrier state in maintaining hosts is that the serotypes are relatively uncommon and are unlikely to be isolated repeatedly as transient infections. These results are consistent if the great bulk of infections recorded represent short-term transient episodes of infection. The few long-term infections may also be maintained by recycling in high infection areas such as contaminated seepage areas and other surface water used by quokkas and cohabiting wildlife converging for drinking. Quokkas have been shown to supplement their meagre supplies of water by drinking brackish water that seeps into the various salt lakes on the island (Jones Bradshaw Fergusson & Watts 1990). During the summer months these seepage areas are heavily contaminated with droppings and 24 different serotypes have been

identified from a total of 219 isolations, suggesting contact with other reservoir hosts, such as reptiles or seagulls (*Larus novaehollandiae*) (Iveson & Bradshaw 1978).

Movements of quokkas

The record of animal movements confirmed that most quokkas were highly sedentary, moving only short distances to foraging areas close to diurnal rest sites (Kitchener 1972). A small number of individuals, however, showed evidence of high mobility, being recaptured at distances over 1 km on the small island. Five quokkas, for example, moved between Kingston Barracks and the camping ground. Forty nine animals (29 males and 20 females) were classified as 'mobile' and 10 of these (20%) were positive and infected with *S. adelaide, S. javiana* and *S. typhimurium* PT 202. Movements were mainly in the settlement areas and included quokkas moving from the beach to the camping area, from Bathurst Point to the Police Station, and from Garden Lake to Bickley Swamp – this latter displacement being approximately 1 km. There was no evidence, however, of quokkas moving short or long distances acting as carriers of *Salmonella* infections to new locations. One quokka sampled in the settlement classified as 'sick' and in poor condition showing evidence of wasting and scouring was positive for *Campylobacter jejuni*, an important zoonotic pathogen. *Edwardsiella tarda*, an opportunistic human pathogen, was also isolated from quokka droppings at Garden Lake.

Population and density estimates

The estimates of population sizes are of necessity only approximate, merging close sites and different collecting dates in order to overcome the problem of small sample sizes. They nonetheless give some idea of the extraordinarily high density of the quokka population in the settlement area. Estimates of the total number of quokkas on Rottnest Island are vague but the figure of 12,000 is accepted by most commentators (Iveson & Bradshaw 1978; Miller & Bradshaw 1979; Pen & Green 1983), giving an average density of 6.3 animals ha^{-1} for the 1912 ha island. This needs to be contrasted, however, with the figure of 21 animals ha^{-1} in the confined settlement area. The settlement area, because of its proximity to humans and supplementary sources of food, is obviously a preferred site for quokkas and this almost certainly adds to the likelihood of their acquiring and recycling infections. Animal densities in the wild of greater than 2 ha^{-1} are unusual – for example in the Niassa Reserve in Mozambique this only occurs in small localised areas with densities of 0.5–2.0 individual ha^{-1} being much more common (Gibson 2000). Population densities at Kingston Barracks/Bickley Swamp and the Geordie Bay and Longreach settlements were lower, but still well above what would be needed to nullify the risk of recycling and re-infection between quokkas.

Implications of the study

Guidelines for the management of salmonellosis on Rottnest Island were established prior to the present study (Iveson & Hart 1983) and quokkas in subsequent year have been effectively excluded from the settlement area that is most frequented by members of the public. This has been done primarily by denying quokkas access to spaces beneath houses and buildings where they previously sought refuge during the daylight hours, emerging to feed at night. The one exception is the tourist bus stop at Lighthouse Swamp which the present study suggests does not pose a significant health risk to the public, as visitors to the site are supervised. These measures appear to have been very effective, with no documented recurrences of human cases of salmonellosis on the Island since 1991.

The study provides insights into the potential hazards of tourist-type facilities that focus on close encounters with wildlife species. Rottnest Island is an iconic resort for West Australians, where escape from the pressures of modern living are sought specifically by a temporary retreat, and rejuvenating contact with nature is a primary aim of the visit (Seddon 1983). The prevalence of a large number of serotypes in a natural population of animals such as the quokka, with infection rates reaching 70% in some areas in the summer months, serves, however, to highlight the inherent dangers of too-close contact with wild species. Outbreaks of salmonellosis that can be traced to wildlife are quite common (e.g. an outbreak of *Salmonella saintpaul* in Queensland that was traced to frogs and mice (Taylor Sloan Morton & Hunter 2000)) and there is a need to educate the public of the importance of respecting wildlife and not treating it as a natural extension of household pets. There is also a need to better understand the source of *Salmonella* infections in mammalian species, where they appear to be at least potentially pathogenic, whereas in some vertebrates, such as reptiles, they appear to be natural members of the gastrointestinal flora.

Acknowledgements: This paper is dedicated to the memory of the late Ray Hart who, as a PhD student of the other two authors, laid the groundwork for our current understanding of the fascinating dynamic nexus between the marsupial quokka and the many *Salmonella* serotypes established on Rottnest Island. Quokkas were collected under licence from the Department of Conservation and Land Management (CALM, now DEC) and the Rottnest Island Authority (RIA) facilitated the study in many ways. The joint investigations were funded by the Public Health Department of Western Australia and the Department of Zoölogy of the University of WA. The authors acknowledge the invaluable contribution to the study of Mr R. Curtis and Mr G. Mofflin.

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A contribution on the biodiversity and conservation of the freshwater fauna of rocky outcrops in the central Wheatbelt of Western Australia

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Manuscript received January 2007; accepted June 2007

Abstract

Rock pools on top of inselbergs are probably the only freshwater biotopes in the Wheatbelt of southwest Western Australia not threatened by salinisation. Their invertebrate fauna is highly diverse, but variation on and between outcrops raises serious difficulties in setting minimum conservation goals to protect the rock pool fauna in the central Wheatbelt. We intensively sampled the invertebrate communities in a large number of pools on Wave Rock (57 pools) and King Rocks (35 pools) near Hyden. To help establish the conservation value of these habitats we present a comprehensive list of species. Overall 66 taxa were found. Sampling of 10 pools on an outcrop is enough to establish the most common species, but even after sampling 57 pools, new species were still being added to the list. We argue for the conservation of several rocky outcrops in different precipitation zones. Outcrops should be selected on the criteria of (a) degree of isolation from the other outcrops, (b) the presence of large and deep pools and (c) whether amphibians breed in the rock pools.

Keywords: conservation, rock pool, gnamma, granitic inselberg, freshwater fauna, biogeography.

Introduction

Freshwater habitats in the Wheatbelt of WA are scarce and disappearing through salinisation (Halse *et al.* 2003; Pinder *et al.* 2004). Probably the single habitat independent from this problem are rock pools on granitic inselbergs, locally known as "gnammas". These "freshwater havens", as Ian Bayly (1992) describes them, are completely rain dependent, support a diverse fauna and flora, and in many cases provide water for humans as well (Laing & Hauck 1997; Bayly 2002). The people of Hyden, a town in the central Wheatbelt in Western Australia, still use the water collected from Wave Rock for drinking and stock water. Two recent symposia (Hopper & Withers 1997; Withers & Hopper 2000) have drawn attention to rocky outcrops, but nonetheless the rock pools in Western Australia remain a poorly studied habitat. Some ecological, but mostly systematic studies, presenting the results of surveys at the community level have been completed (Bayly 1982 1997; Pinder *et al.* 2000). These studies found strong differences in species richness in pools on and between rocky outcrops. Differences in species richness between outcrops in WA are related to regional precipitation patterns, affecting the length of the inundation period (Jocqué *et al.* unpublished data). The length of the inundation period in temporary waters is probably the single most important factor determining the structure and richness of a community (Wellborn *et al.* 1996). The heterogeneous environment (*i.e.,* variation in depth, size, sediments, vegetation, in-pool boulders) of the pools further results in a diverse group of species occurring on a single outcrop (Pinder *et al.* 2000). The rich and diverse aquatic invertebrate fauna combined with the large proportions of endemic inhabitants in these rock pools (Frey 1998) and the vulnerability of temporary (freshwater) habitats in arid Australia (Roshier *et al.* 2001) urge the protection and conservation of these rock pool habitat systems. The high diversity on and between outcrops poses serious difficulties in setting minimum conservation goals to protect the rock pool fauna in this region and Pinder *et al.* (2000) made a plea for more intensive studies of Wheatbelt outcrops to obtain a better idea of the distribution of rock pool inhabitants. To help establish the conservation value of these habitats we present a species list from an intensive survey of 57 pools on Wave Rock and an extensive survey of 35 pools on King Rocks. A more detailed analysis of the data will be published elsewhere.

Material and Methods

Study site

The rock pools sampled were situated on Wave Rock (57 pools) near the town of Hyden and King Rocks (35 pools) approximately 50 km northeast of Wave Rock (Fig. 1) We sampled the pools in the winter of 2004 from 8th of July to 29th of August.

Sampling protocol

Two sampling methods were used to collect the

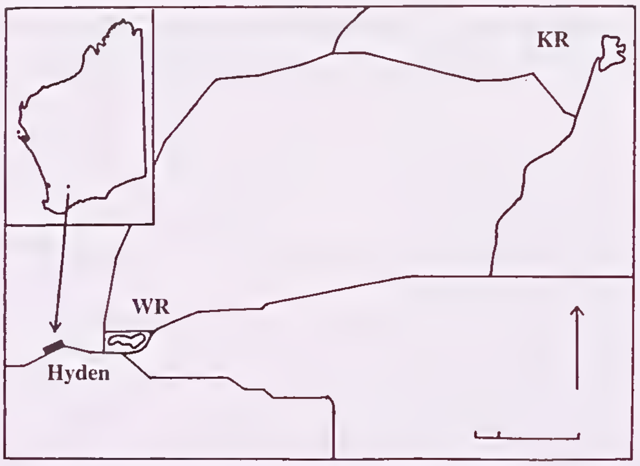

Figure 1. Map with the exact location of Hyden, the inselbergs Wave Rock (WR) and King Rocks (KR) in Western Australia. The lines indicate the major roads in the area. The scale indicates 5 km.

organisms, the first procedure aimed at the smaller benthic organisms and the second procedure was performed to collect the larger macro-invertebrates missed by the first sampling method. Benthos samples were taken by placing a plastic rectangular frame enclosing a surface of 0.5m² randomly in the pool. The water was stirred thoroughly to lift all the benthic organisms. The calculated volume of the enclosed water was subsequently removed with a plastic one litre measuring cup and poured through a 64µm filter. The filtered content was then preserved in 70% ethanol. This was done once for small pools, twice for medium sized pools and three times for large pools and aimed at sampling roughly 10% of the surface of the pools. On King Rocks there was time to sample only nine of the 35 pools by this method.

The second sampling method was done with a 500-µm kicksampler. Between 5 and 30 kicks were executed with the same speed and covering the same distance, aiming at covering the whole surface of the pool once. Macroinvertebrates were partly picked out in the field and the sample residuals were preserved in 70 % ethanol and double checked for presence of animals in the lab. Samples were screened in the lab for macroscopic organisms and identified as far as possible under an OLYMPUS SZ-X 12 stereo-microscope. All studied pools on both outcrops were sampled by this method.

In this study, the species list (Table 1) is compiled simply on a presence/absence basis and the cumulative richness curve (Fig. 2) is based on 999 permutations of the Wave Rock data. Due to identification uncertainties, Chironomidae (at least five taxa) as well as *Alona* (2), *Ephemeroporus* (2), *Paroster* (2), *Limnocythere* (3) and *Macrotrix* (2) are each treated as a single taxon in the graph.

Results

We found 58 and 43 taxa in the rock pools on Wave Rock and King Rocks, respectively, and 66 taxa overall (Table 1). The most speciose groups in our study were Coleoptera (15), Cladocera (13), Ostracoda (12) and Diptera (10). The most common organisms were the ostracod *Cypretta baylyi* and the endemic cladoceran *Neothrix armata*, both occurring in 51 of the sampled pools. Although not identified to species level, Chironomidae and Turbellaria were present in 55 and 48 of the sampled pools and are also a major component of the rock pool communities. The rare taxa in these systems occurring in only one, or two pools were all Insecta (*Necterosoma penicillatus*, Tipulidae, *Rhantus* sp., *Limnoxenus zelandicus*, *Micronecta gracilis*) as well as a gastropod (*Glyptophysa* sp.) and a cladoceran (*Planicirclus alticarinatus*).

On average we found 18.7 ± 5.0 taxa in the rock pools on Wave Rock. Most of the common species occurring on Wave Rock were found after the sampling of 10 rock pools. Although the slope of the Cumulative Species Richness curve (Fig. 2) decreased with increasing number of pools, the curve did not plateau.

Discussion

More species were found on Wave Rock than King Rocks (57 as against 43), probably because of the lower sampling effort on King Rocks. In fact King Rocks has more pools and bigger pools (see later) than Wave Rock, so it is likely it has more species. Our figures for species richness compare with the average 48.9 taxa in the study by Pinder *et al.* (2000). Their highest taxon richness (77 at Wanara Rock), was much higher than ours, but this rock was advantaged by having a deep (50cm) artificially dammed pool with macrophytes that is normally wet for much of the year (B. Turner pers. comm.). A long inundation cycle in temporary pools is one of the most important factors determining the composition and structure of communities (Wellborn *et al.* 1996). A longer inundation cycle, removes the developmental constraints which could prevent some organisms occurring in the most temporary pools (*e.g.,* Odonata), allows for a transition of taxa (succession) and also provides a refuge for actively dispersing insects with an adult aquatic phase such as several Hemiptera. The richness values for

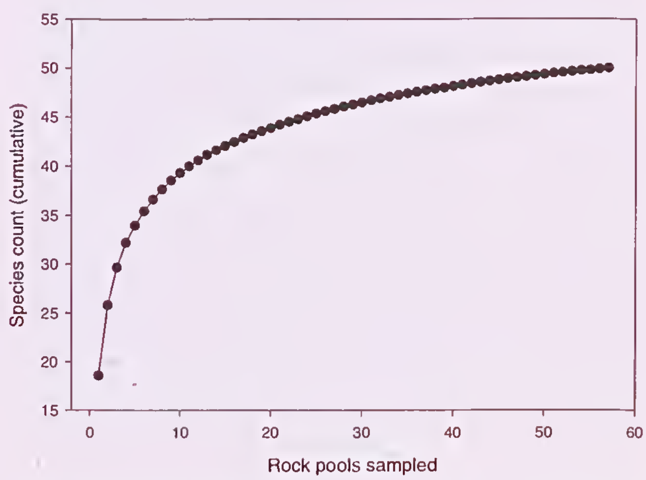

Figure 2. Cumulative species richness curve for 57 rock pools sampled on Wave Rock.

Table 1

Taxa collected from rock pools on Wave Rock and King Rocks. Identification of the underlined Cladocera was not confirmed N. Smirnov. * not caught in this study, but known to be present most years, ^ species restricted to granitic gnammas

Major group	Family	Species	WR	KR
Turbellaria			x	x
Spinicaudata	Limnadiidae	*Limnadia badia*^	x	x
	Cyzicidae	*Caenestheriella mariae*^		x
Anostraca	Branchinellidae	*Branchinella longirostris*^	x*	x
Copepoda	Centropagidae	*Boeckella opaqua*^	x	x
	Harpacticoida		x	x
Cladocera	Chydoridae	*Alona macrocopa*	x	x
		<u>*Alona rigidicaudis*</u>	x	
		Plurispina multituberculata^	x	x
		Leberis aenigmatosa	x	x
		<u>*Planicirclus alticarinatus*</u>	x	
		<u>*Ephemeroporus hybridus*</u>	x	
		Ephemeroporus barroisi	x	x
		Pseudomonospilus diporus	x	
	Macrotricidae	*Neothrix armata*	x	x
		Macrothrix breviseta	x	
		Macrothrix hardingii^		x
	Daphniidae	*Ceriodaphnia* sp.		x
	Moinidae	*Moina* sp.	x	
Ostracoda	Cyprididae	sp. A	x	x
		sp. B	x	
		Limnocythere sp. A	x	
		Limnocythere sp. B	x	x
		Limnocythere cf *porphyretica*	x	
		Limnocythere mowbrayensis	x	x
		Ilyodromus amplicolis	x	x
		Candonocypris incosta	x	x
		Candonocypris sp. A	x	
		Cypretta baylyi	x	x
		Bennelongia barangaroo	x	x
		Sarscypridopsis sp. A	x	
Odonata	Corduliidae	*Hemicordelia tau*	x	x
	Lestidae	*Austrolestes* sp.		x
Hemiptera	Corixidae	*Agraptocorica parvipunctata*	x	x
		Micronecta gracilis	x	x
	Notonectidae	*Anisops thienemanni*	x	x
Trichoptera	Leptoceridae	*Triplectides* sp.		x
Coleoptera	Dytiscidae	*Allodessus bistrigatus*	x	x
		Sternopriscus multimaculatus	x	x
		Paroster michaelseni	x	
		Paroster niger	x	
		Lancetes lanceolatus	x	
		Rhantus sp.	x	
		Antiporus gilberti	x	x
		Hyphydrus sp.		x
		Necterosoma penicillatus	x	
		Megaporus howitti		x
	Hydrophilidae	*Limnoxenus zelandicus*	x	
		Enochrus maculiceps	x	
		Berosus nutans	x	
		Berosus discolor	x	
		Berosus approximans	x	
Diptera	Chironomidae	*Orthoclad* sp.	x	x
		Paraborniella sp.	x	x
		Cryptochironomus sp.	x	x
		Dicrotendipes sp.	x	x
		Forcypomyninae sp.	x	x
	Culicidae	*Aedes alboannulatus*	x	x
	Ceratopogonidae		x	x
	Sciomyzidae		x	x
	Tabanidae		x	
	Tipulidae		x	x
Gastropoda	Planorbidae	*Glyptophysa* sp.	x	x
		Isidorella sp.		x
Acari	Caeculidae?		x	x
Anura		*Crinia* sp.	x	x

the outcrops presented from Pinder *et al.* (2000) are also not directly comparable to our figures as these authors included Protozoa, Rotifera and Oligochaetes in their list and most Diptera (generally the most speciose group) were identified to species, whereas we omitted these groups and incompletely identified dipterans. However the dominant taxonomic groups in both studies were comparable, but often slightly richer in our study — Coleoptera (15 taxa versus 12 taxa), Cladocera (13 versus 11) and Ostracoda (12 versus 12). The higher richness in our study most probably is a direct result from the sampling intensity: Pinder *et al.* (2000) sampled around 10 pools whereas we sampled 57 pools on Wave Rock.

The only species we added to the list of Pinder *et al.* (2000) were the beetle *Hyphydrus,* the small crustaceans *Ephemeroporus hybridus* and *Candonocypris incosta,* the listing of what was previously identified as *Cyzicus* as *Caenestheriella mariae* and the further identification of *Limnadia* as *L. badia* (see Timms, 2006). As Pinder *et al.* (2000) found, many species occurred in only a few pools, a phenomenon with implications for sampling intensity and conservation policies (see later).. The list will grow by increasing the search area and by more detailed identifications, particularly of the Turbellaria, Oligochaeta (*e.g.,* Pinder, 2003) Tardigrada, Nematoda and Mesostigmatid and Trombidoid mites. One particular difficulty in this is the large morphological variation between populations of passive dispersers on different outcrops. A studied example is the fairy shrimp *Branchinella longirostris* with large morphological variations between populations on a series of outcrops from the south to the north of WA (M. Zofkova & B. Timms, unpublished data).

Six species (10%) on our list are endemic to granitic gnammas (Table 1). For the Wheatbelt as a whole the figure is about 30 species (13%) (Pinder *et al.* 2000, 2004; A. Pinder pers.com.). The difference might be due to the much larger area covered by Pinder *et al.* (2000). Rock pool specialists such as the various branchiopods, ostracods and cladocerans are typically passive dispersers. These passive dispersers do not have the ability for active dispersal to another habitat patch and are dependent on other media such as wind (Brendonck & Riddoch 1999) and water (Brendonck *et al.* 1998). This results in strong dispersal limitation of populations between outcrops, so that the populations over time each evolve in their own direction and might differentiate to different species. Long-distance dispersal limitation in this habitat type in Botswana was found for *Branchipodopsis wolfi* (Anostracan) by Hulsmans *et al.* (2007) and probably applies also to the fairy shrimp and possibly other passive dispersers of local rock pools.

The active dispersers such as beetles and corixids are often generalist species of temporary waters with high dispersal capacities and easily spread over large areas, and also not particularly restricted to rock pools (Jocqué *et al.* 2006). In particularly wet winters as in our study period, pools have a relatively long inundation cycle and the longer exposure time results in more species and species from (more) permanent water bodies, which are absent in drier years (Jeffries 1994).

Despite the occurrence of the frequently encountered species discussed above, the most characteristic inhabitants of these gnammas are indeed the large branchiopods —Spinicaudata, together with Anostraca and Notostraca (Bayly, 1997; Timms, 2006). While the spincaudatan *Limnadia badia* was common and widespread, this study hardly encountered another clam shrimp (*Caenestheriella mariae*) and fairy shrimp *Branchinella longirostris,* yet in other years both were common (Timms 2006, and unpublished data). Anostraca are specialists of temporary pools and highly sensitive to predation, mostly from insects immigrating to the pools (Brendonck *et al.* 2002). Increasing predator pressure over time reduces Anostracan populations and could explain why *B. longirostris* completes its life cycle early in a pool's seasonal existence, so that after a few weeks individuals are no longer present. In 2004 the pools of Wave Rock filled early in the season (April–May), but in 2006 they filled late (July). In 2004, none were present on Wave Rock in August (Table 1), but in 2006 most pools had extant populations (Timms, unpublished data).

Pinder *et al.* (2000) did not mention any Anura. In several pools we found large densities of tadpoles of *Crinia* sp. Tadpoles may have an important role in rock pools as competitors or predators and they are also known to increase the nutrient availability in a rock pool by processing the sediment (Osborne & McLachlan 1985) and hence indirectly influence the primary productivity and richness of the community. Besides their ecological role, the presence of amphibians in rock pools also has serious implications for conservation. Amphibian diversity in Australia and on a global scale is declining dramatically (Pechmann & Wilbur 1994). When evaluating the conservation value of a rock pool system, attention should be devoted to the presence and diversity of amphibian populations.

The cumulative richness curve shows that the most common species are collected after sampling about 10 pools. This was the sampling intensity used by Pinder *et al.* (2000) and it provides information on the core species of the system and allows a good estimate of the total richness on these outcrops. If more complete information is needed on the diversity in a rock pool system, a large number of additional pools should be sampled. Most of the rare species collected on Wave Rock occurred in one of the deeper (and often also larger) pools with more permanent inundation, indicating that for an intensive sampling campaign aimed at finding the rare species in a rock pool system, it is best to focus on these deeper and larger pools, if present. However it should be noted that most of the rare species occurring in the pools with a longer inundation cycle are insects (*e.g.,* almost all were beetles and odonates) and appear to be generalist species of temporary habitats, also occurring in other types of freshwater wetlands. The later are declining in availability in the Wheatbelt of WA (Halse *et al.,* 2003), so that gnammas are becoming more important in their survival, but it is the crustaceans unique to gnammas for which this habitat should be evaluated to establish the primary conservation value.

As shown above, the rock pools and the entire rocky outcrops are unique habitats with a high diversity of specialist and endemic species. Protection of these habitats is essential but establishment of a conservation strategy will not be straightforward (Mawson 2000). The strong isolation of the communities on these outcrops potentially makes them sensitive for extinctions through

human disturbance, climatic or stochastic events (Bussell & James 1997). If a species disappears on an outcrop it might take a while before it returns through a successful colonization and this most probably to a large extent explains a large part of the heterogeneity of communities on the different outcrops. The best approach would be to conserve a considerable number of outcrops scattered over a large area. At present relatively few granite outcrops lie in National Parks and/or Nature Reserves, though many like Wave Rock and King Rocks, enjoy a degree of protection as water catchments or for recreation. Terrestrial habitats on many granite rocks are compromised by human activities (Main 1997), though it seems to us that the pool environments are less affected and indeed are often pristine Even the intensive use of Wave Rock as a tourist destination seems largely not to have degraded the pools, though luckily most of the pools on Wave Rock are not on the main tourist routes across the rock. For a complete conservation of assemblages in gnammas, rocks should encompass a regional variation in climate-related variables, directly affecting the length of the hydroperiod, and related to this, the richness of the community. Based on the average length of the hydroperiod, it might be interesting to invest slightly more value to some of the outcrops in higher precipitation zones. Based on our experience at Wave Rock this will increase the more widely occurring species, often non-endemic active dispersers. To more adequately characterize the endemic passive dispersers, attention should be at the other end of the scale as most seem to be strongly adapted to temporary pools and not present in the higher rainfall zones. Examples include oligochaetes (Pinder 2003) and large branchipods (Timms, 2006). Two concerns should be mentioned; strongly isolated communities (far from other outcrops) most probably will hold some special rare species and if in the future climatic conditions shift, and especially precipitation zones and evaporation rates, then also the value of the established protected outcrops will change (with the changing length of the inundation period). A good strategy to follow now might be 1) an evaluation based on a thorough survey of the aquatic fauna present in the currently protected Nature Reserves such as Boyagen Rock, Yorkakrine Rock, Frog Rock, Cairn Rock, Dunn Rock and Yanneymooning Rock, 2) addition of other outcrops to the reserve system, aiming to include species not present on the already protected rocks and 3) appropriate management of rocks outside the reserve system by landholders and other interested parties.

Acknowledgments: Merlijn Jocqué is supported by an IWT (Institute for the Promotion of Innovation by Science and Technology in Flanders) PhD scholarship. This research is financially supported by project G.0118.03 of the FWO (Fund for scientific Research in Flanders). A travel scholarship was provided by the King Léopold III Fund for Nature Exploration and Conservation. We thank Nicolai Smirnov (Cladocera), Christopher Watts (Coleoptera), Koen Martens and David Horne (Ostracoda), Cameron Webb (Culicidae), Winston Ponder (Gastropoda) and Rosalind St Clair (Trichoptera) for help with identifications. We thank the residents from Hyden for their warm welcome and the science friendly environment. In particular we are grateful to the late Russell Mauritz and family for providing accommodation during our stay and ready access to Wave Rock. We are grateful to Ian Bayly and Adrian Pinder for helpful comments on the manuscript. Merlijn Jocqué is a founding member of BINCO (Biodiversity Inventory for Conservation).

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Validation of the AUSGeoid98 model in Western Australia using historic astrogeodetically observed deviations of the vertical

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Manuscript received March 2007; accepted May 2007

Abstract

AUSGeoid98 is the national standard quasigeoid model of Australia, which is accompanied by a grid of vertical deviations (angular differences between the Earth's gravity vector and the surface-normal to the reference ellipsoid). Conventionally, co-located Global Positioning System (GPS) and spirit-levelling data have been used to assess the precision of quasigeoid models. Here, we instead use a totally independent set of 435 vertical deviations, observed at astrogeodetic stations across Western Australia before 1966, to assess the AUSGeoid98 gravimetrically modelled vertical deviations. This point-wise comparison shows that (after three-sigma rejection of 15 outliers) AUSGeoid98 can deliver vertical deviations with a precision (standard deviation) of around one arc-second, which is generally adequate for the reduction of current terrestrial-geodetic survey data in this State.

Keywords: geodesy, vertical deviations, quasigeoid, geodetic surveying, geodetic astronomy

Introduction

Gravimetric quasigeoid models are commonly validated on land using co-located Global Positioning System (GPS) and spirit-levelling data (*e.g.*, Featherstone 1999, Featherstone & Guo 2001, Featherstone *et al.* 2001, Amos & Featherstone 2003). However, this approach suffers from correlations among the data and deficiencies in the local vertical datum, which is especially the case for the Australian Height Datum (Featherstone 1998, 2004, 2006; Featherstone & Stewart 1998; Featherstone & Kuhn 2006). A better validation can be achieved by using deviations of the vertical (*cf.* Jekeli, 1999; Hirt & Seeber 2007), which are observed using different principles and thus are totally independent of the vertical datum (*cf.* Featherstone, 2006).

The deviation (or sometimes deflection) of the vertical is the angle between the Earth's gravity vector and the surface-normal to the reference ellipsoid (Bomford 1980, and Fig. 1). Since the plumblines (field lines) of the Earth's gravity field have both curvature and torsion, due varying mass-density distributions inside the Earth, the deviation of the vertical is a function of 3D position. The two main sub-classes of vertical deviation are (Jekeli 1999): Pizetti deviations at the geoid (essentially the undulating mean sea level surface; Featherstone 1999), and Helmert deviations at the Earth's surface.

The total vertical deviation (θ) in Figure 1 is further decomposed into north-south (ξ) and east-west (η) components. These are needed in the reduction of terrestrial-geodetic survey data to the reference ellipsoid (Featherstone & Rüeger 2000)

Vertical deviations can either be observed geodetically or computed from gravity data. Helmert vertical deviations are observed from the difference between astronomical latitude (Φ) and longitude (Λ) and geodetic latitude (φ) and longitude (λ), with the latter scaled by meridional convergence. Astronomical or natural coordinates are derived from timed angular measurements to the stars (*e.g.*, Bomford 1980; Hirt & Seeber 2007 Hirt & Flury 2007). Geodetic coordinates are derived from geodetic surveying observations, e.g., angles, distances and GPS. Pizetti deviations can be computed from gravity data using Vening-Meinesz's integral (*e.g.*, Heiskanen & Moritz 1967; Kearsley 1976) or from horizontal gradients of a geoid model (cf. Figure 1), which is the approach taken here. All the relevant formulas are given in Featherstone & Rüeger (2000).

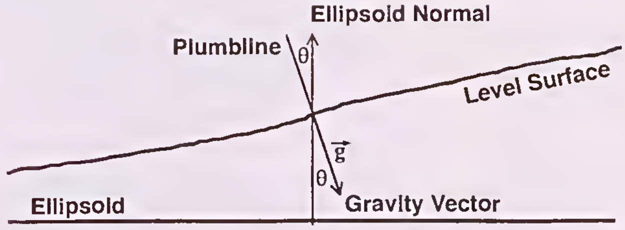

Figure 1. A generalised schematic of the deviation of the vertical, where the plumbline is perpendicular to the level surface, thus the deviation is a measure of the slope of the level surface with respect to the ellipsoid.

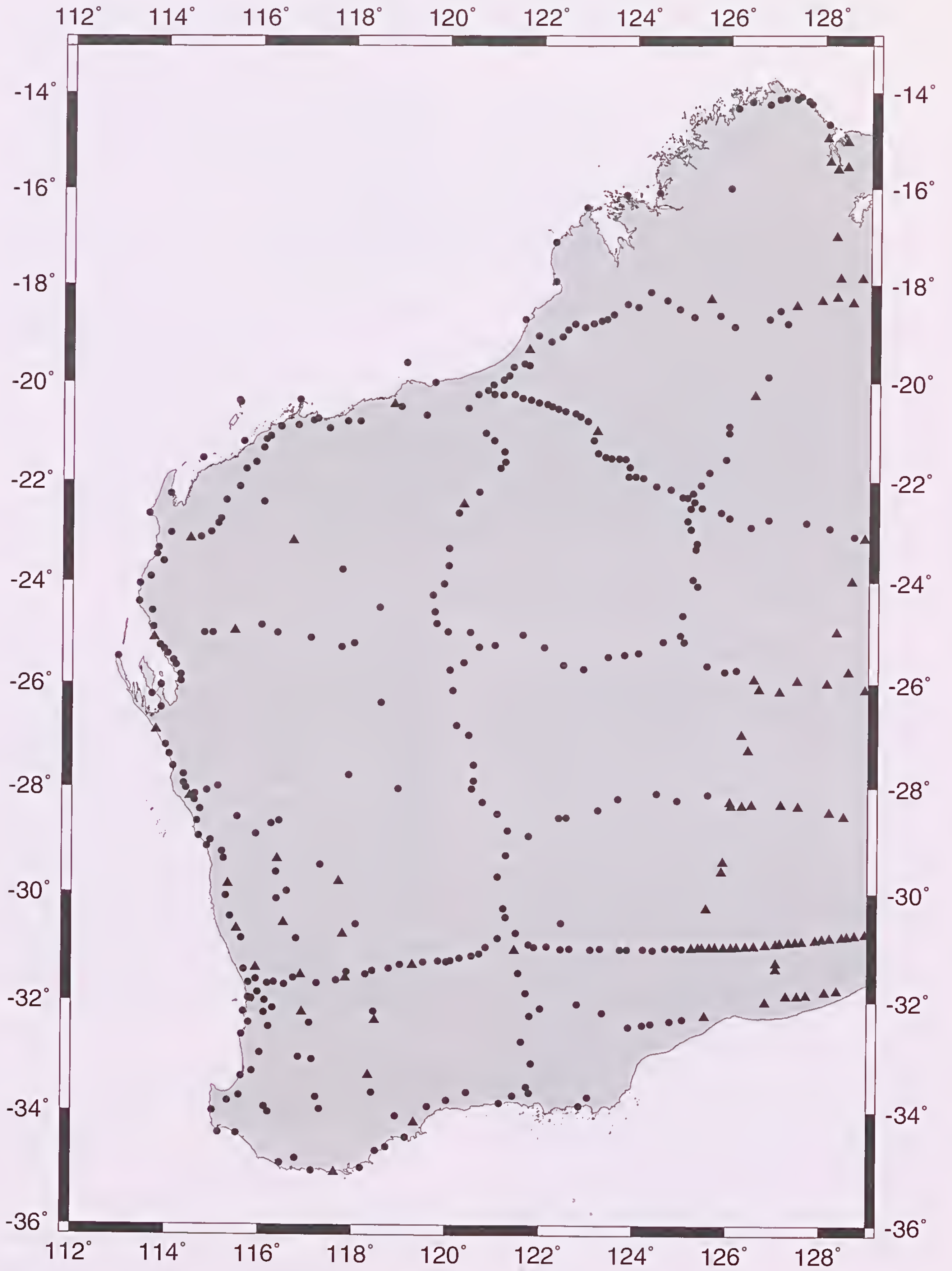

Figure 2. Locations of the observed astronomic-Helmert vertical deviations across Western Australia (Mercator projection). Triangles denote sites used by Featherstone (2006); circles denote the new sites.

Vertical deviations are of practical importance in high-precision terrestrial-geodetic surveying (Featherstone & Rüeger 2000), which has now become more important because of the introduction of the Geocentric Datum of Australia (GDA94) (ICSM 2002). The AUSGeoid98 gravimetric quasigeoid model (Featherstone *et al.* 2001) is accompanied by a regular two-arc-minute grid of vertical deviations, which were computed from horizontal„quasigeoid gradients in the north-south and east-west directions.

Strictly, the Pizetti vertical deviations should be computed from the horizontal gradients of a geoid, not quasigeoid, model because a quasigeoid does not model equipotential (level) surfaces of the Earth's gravity field (*cf.* Jekeli 1999). The differences are correlated with height and Bouguer gravity anomaly (*e.g.*, Rapp 1997). However, AUSGeoid98 is not strictly a quasigeoid model because some terms were approximated, notably the Molodensky G1 term (*e.g.*, Heiskanen & Moritz 1967) by the linear Morizian terrain correction (Featherstone *et al.* 2001). The difference between the geoid and quasigeoid over Australia only reaches 15 cm and varies relatively smoothly (Featherstone & Kirby 1998). Therefore, this effect on the vertical deviations will be small, probably less than one arc-second (discussed later).

Comparing observed and computed vertical deviations is an independent way of validating the latter (*cf.* Featherstone 2006, 2007). In this paper, we use a recently released set of additional vertical deviations over Western Australia to validate the performance of the AUSGeoid98 gravimetric vertical deviations. As pointed out in Featherstone (2007), most of the Western Australian data were omitted in Featherstone (2006). Of the 435 vertical deviations across Western Australia, only 96 were used by Featherstone (2006).

Data, Methods and Results

Observed astronomic-Helmert vertical deviations

A set of 339 vertical deviations has recently been released by Landgate (formerly the Western Australian Department of Land Information). These are from the State's geodetic network at sites that have co-located geodetic and astronomic observations. The astronomic observations were made before 1966 to provide azimuth control (orientation) to the long-line traverses used to establish the old Australian Geodetic Datum 1966 (Bomford 1967).

Landgate extracted the GDA94 geodetic coordinates of these points, which allowed the computation of the vertical deviations with a fairly good geographical distribution across the State (Fig. 2). The formulas for computing vertical deviations from astronomical latitude (Φ) and longitude (Λ) and geodetic latitude (φ) and longitude (λ) are given in, *e.g.*, Featherstone & Rüeger (2000) and Jekeli (1999) so will not be duplicated here. Since the astronomic observations are made at the Earth's surface, this yields Helmert deviations.

The accuracy of these astrogeodetic deviation data is difficult to ascertain (*cf.* Featherstone, 2006), principally because of errors in timing measurements of the astronomic longitude observations collected over four decades ago. A crude estimate of the standard deviation in each of the north-south (ξ) and east-west (η) vertical deviation components is about one arc-second. Kearsley (1976) highlights problems of using astrogeodetic deflections because of 1–2 arc-second systematic errors, while achieving precisions of 0.6 arc-seconds. Unfortunately, little information remains about the original observations, but most were probably collected with Kern DKM3 theodolites available before 1966.

Computed AUSGeoid98 vertical deviations

AUSGeoid98 (Featherstone *et al.* 2001) vertical deviations are provided in the data files released by Geoscience Australia, as well as the primary dataset of quasigeoid heights. An accompanying public-domain Windows™ program, WINTER v5.08, bicubically interpolates these vertical deviations from the regular two arc-minute grid to the points of interest. WINTER and the AUSGeoid98 data files are freely available from Geoscience Australia (http://www.ga.gov.au/geodesy/ausgeoid/).

Figures 3 and 4 show the vertical deviations computed from AUSGeoid98. Since they are derived from regional gravity data, geological features are evident (*cf.* Featherstone, 1997), most noticeably the Darling Fault close to the Western Australian south west coast (~116° E in Figure 3), the eastern portion of the Albany-Fraser Orogen (from ~33° S, ~122° E to ~29° S, ~125° E in Figures 3 and 4) and the western MacDonald Ranges (~25° S, ~128° E in Figure 4). Other geological features are visible, but this is not the aim of this article; see Featherstone *et al.* (2000) instead.

The AUSGeoid98-derived vertical deviations refer to the quasigeoid. Therefore, they are not strictly Pizetti deflections, as discussed earlier, but the difference is probably less than one arc-second. The difference between Helmert and Pizetti deviations is due to the curvature and torsion of the plumbline through the topography, which depends on the height of the observation point (Jekeli 1999). As discussed in Featherstone (2006), since the topography in Australia is generally benign, the curvature and torsion effect is likely to be less than one arc-second, which is less than the estimated precision of the astronomically observed deviations.

Thus, for the purposes of this evaluation, plumbline curvature and torsion and differences between quasigeoid-derived and geoid-derived Pizetti deviations are neglected. This assumption will be validated later.

Comparisons

The observed astronomic-Helmert deviations were compared with the AUSGeoid98-derived deviations. The astronomic-Helmert deviations were computed from coordinates in Landgate's database according to the formulas in Featherstone & Rüeger (2000). The GDA94 geodetic coordinates of these points were used to bicubically interpolate the AUSGeoid98 vertical deviations using the WINTER v5.08 software.

Table 1 shows descriptive statistics of the differences (astronomic minus gravimetric), both with (Table 1a) and without (Table 1b) 15 outliers as detected by the three-

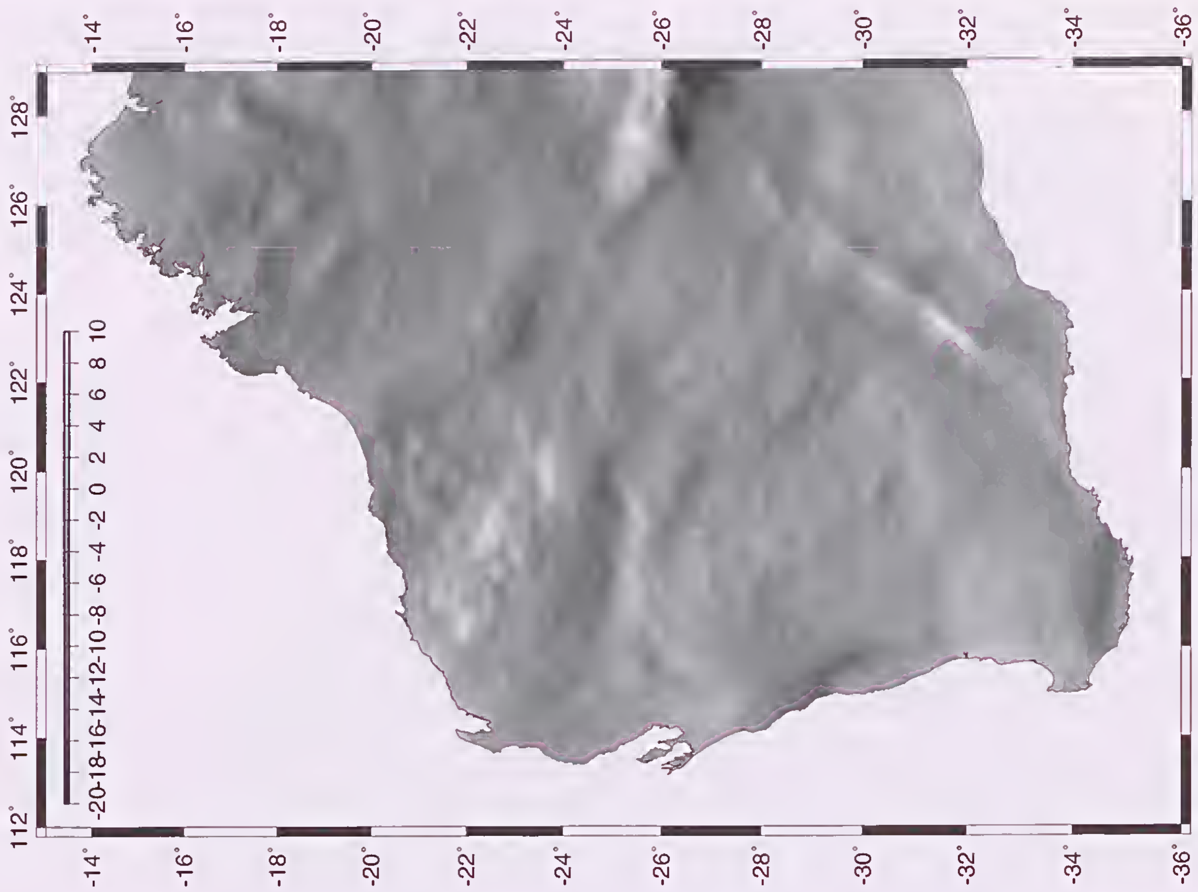

Figure 4. Computed AUSGeoid98 north-south vertical deviations across Western Australia (Mercator projection; Units in arc-seconds).

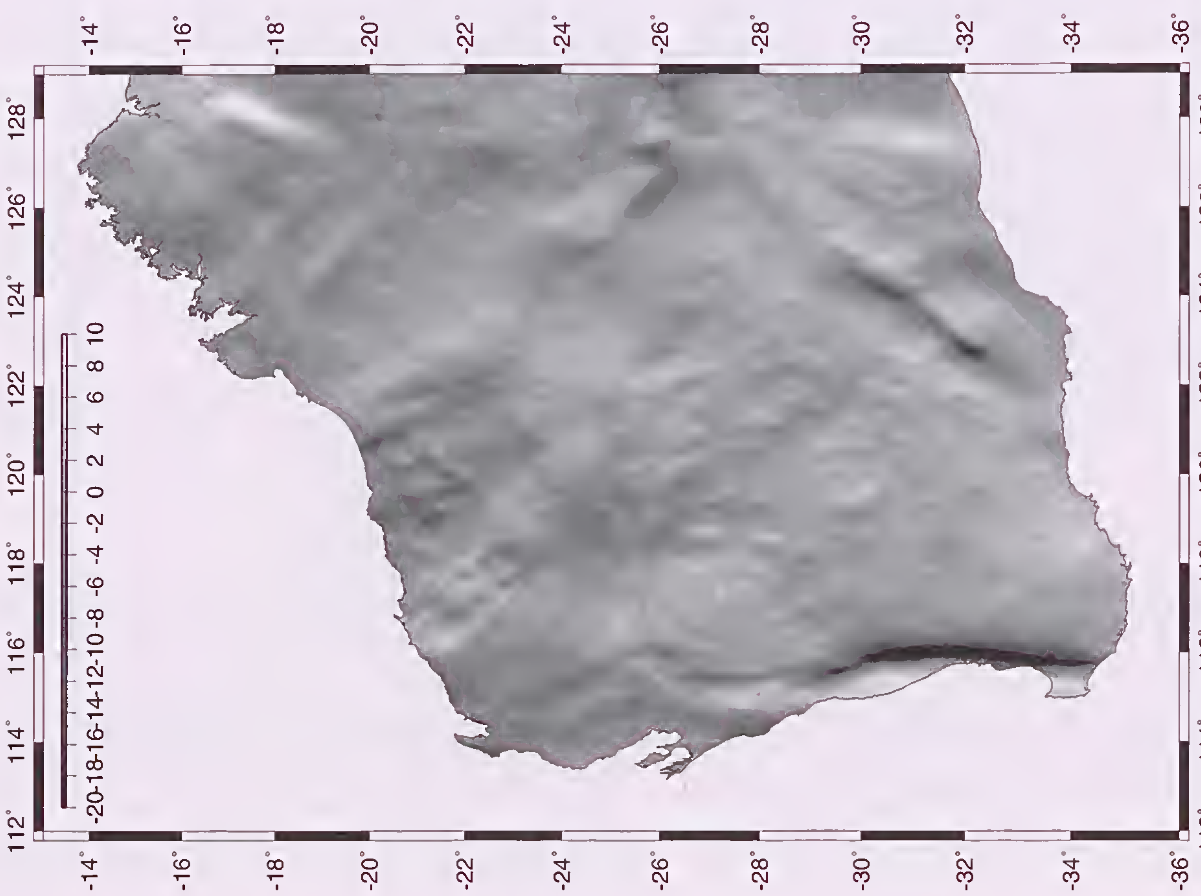

Figure 3. Computed AUSGeoid98 east-west vertical deviations across Western Australia (Mercator projection; Units in arc-seconds).

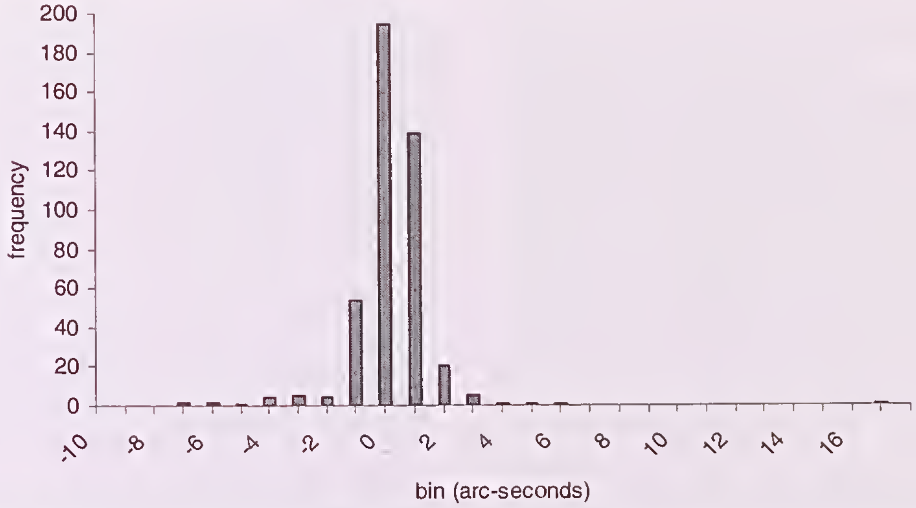

Figure 5. Histogram of the differences between astronomic-Helmert deviations and AUSGeoid98-derived deviations in the north-south component (435 points). Units in arc-seconds.

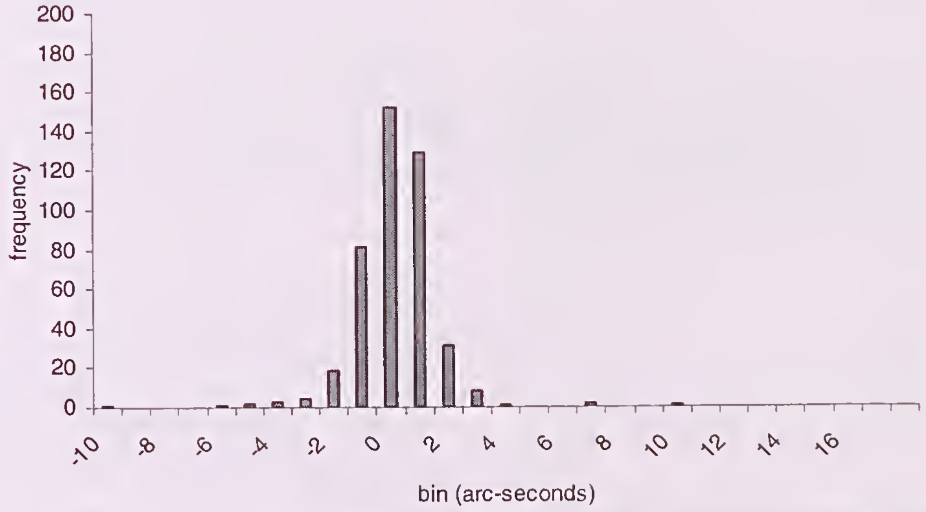

Figure 6. Histogram of the differences between astronomic-Helmert deviations and AUSGeoid98-derived deviations in the east-west component (435 points). Units in arc-seconds.

sigma test assuming a normal distribution of the deviation differences. Figures 5 and 6 show histograms of the differences (including outliers), which are near-normally distributed, thus justifying the use of the three-sigma test for outlier rejection. If one deviation component was determined as an outlier, then both components were rejected. However, around 10 of the outliers were in both deviation components.

Discussion

The results in Tables 1a and 1b largely mirror those in Featherstone (2006); after the removal of outliers (based on the three-sigma criterion), the precision of AUSGeoid98-derived vertical deviations in Western Australia is roughly one arc-second. Indeed, this is commensurate with the estimated precision of the astronomically determined deviations. From the error analysis in Featherstone & Rüeger (2000), this is adequate for the reduction and post-processing of current terrestrial-geodetic survey observations. As such,

Table 1a

Descriptive statistics of the differences between astronomic-Helmert deviations and AUSGeoid98-derived deviations (435 points, including 15 outliers). Units in arc-seconds

	North-south (ξ)	east-west (η)
Maximum	16.9	9.1
Minimum	-7.8	-10.9
Mean	-0.3	-0.3
STD	1.5	1.5

Table 1b

Descriptive statistics of the differences between astronomic-Helmert deviations and AUSGeoid98-derived deviations (420 points, excluding 15 outliers). Units in arc-seconds

	North-south (ξ)	east-west (η)
Maximum	3.0	3.3
Minimum	-4.7	-4.6
Mean	-0.2	-0.3
STD	0.9	1.1

geodetic surveyors in Western Australia are well-served by AUSGeoid98.

The outliers, acknowledging the simplicity of the three-sigma test, should not be treated blindly. It is conceivable that the curvature and torsion of the plumbline is larger than anticipated. For instance, in areas of complex geology or high elevation, it is conceivable that mass-density contrasts will cause large curvature and torsion in the plumbline or steep gravity field gradients that are not be modelled by AUSGeoid98. A key example is in the proximity of the Darling Fault, where low-density sediments juxtapose the high-density Yilgarn Craton.

Kearsley (1976) shows that gravimetric vertical deflections, computed using Vening-Meinesz's integral, are highly sensitive to nearby gravity anomalies, which themselves are greatly affected by the topography.

In order to test this and to ascertain any effect of using quasigeoid, rather than geoid, gradients to approximate Pizetti vertical deviations, the north-south and east-west deviation differences (astronomic minus gravimetric) are plotted as a function of Australian Height Datum (AHD) height of the astrogeodetic stations (Figures 6 and 7). Unweighted linear regression, coupled with the correlation coefficient (R-squared statistic), show that the differences are uncorrelated with AHD height. This observation justifies the earlier assumptions that the curvature and torsion of the plumbline are negligible in Western Australia and the use of the quasigeoid as opposed to geoid to compute Pizetti vertical deflections is acceptable, certainly in relation to the expected one arc-second precision of the astrogeodetic vertical deflections. It also shows that using quasigeoid gradients, as opposed to Vening-Meinesz's integral, is less sensitive to the topography (*cf.* Kearsley 1976).

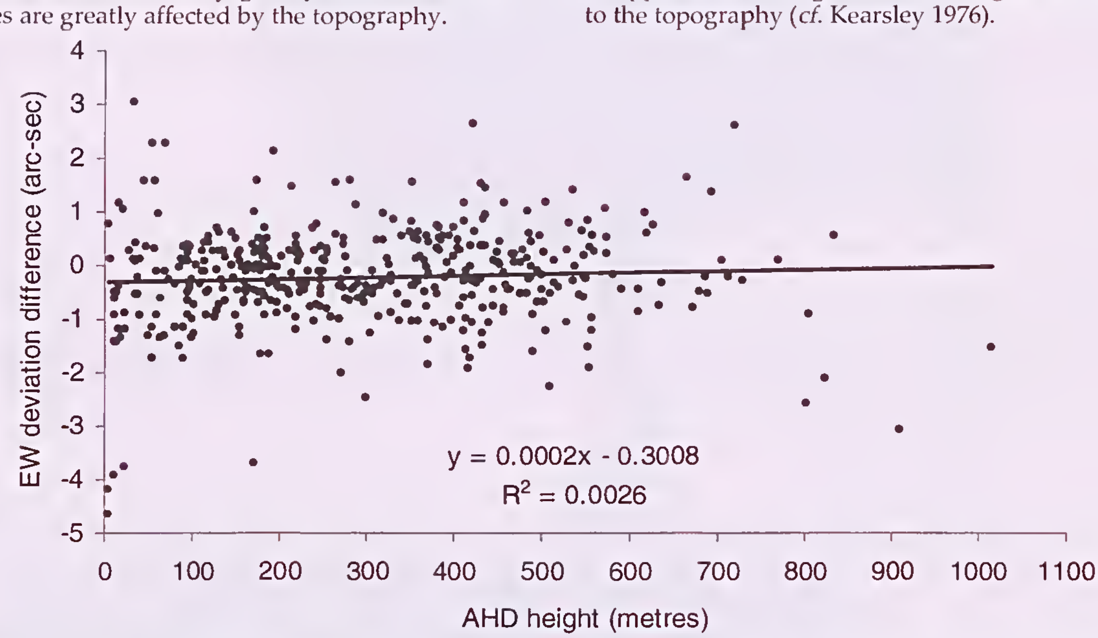

Figure 7. Differences between astronomic-Helmert deviations and AUSGeoid98-derived deviations in the east-west component as a function of AHD height (420 points).

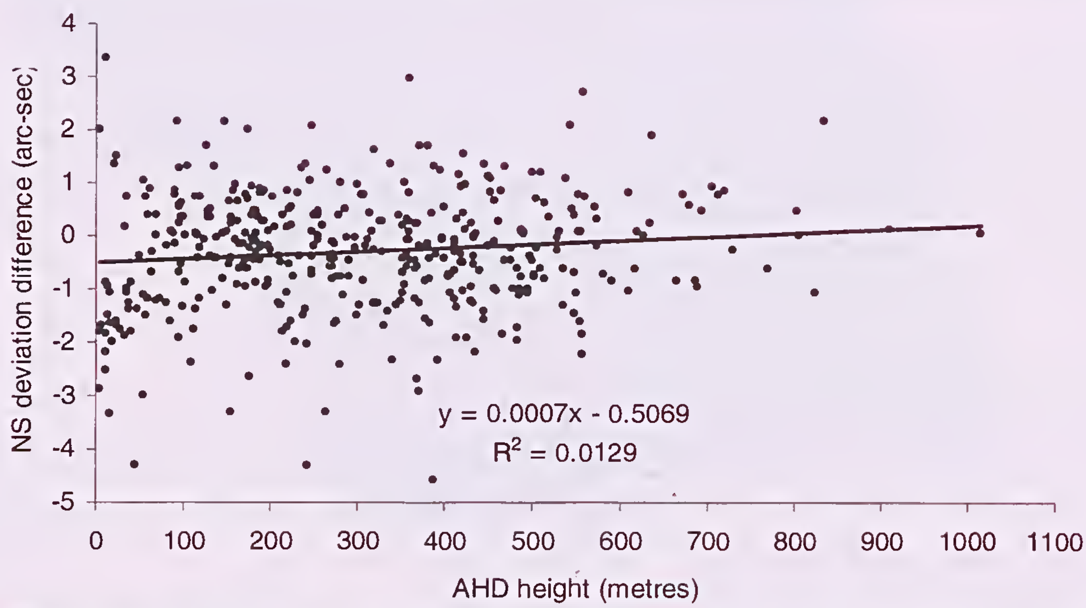

Figure 8. Differences between astronomic-Helmert deviations and AUSGeoid98-derived deviations in the north-south component as a function of AHD height (420 points).

Given that the assumptions about the plumbline and quasigeoid have no appreciable effect, timing errors in the original (before 1966) astronomical longitudinal observations (*cf.* Kearsley 1976) are a more plausible cause of the observed differences. This is implied in Table 1b, where – even after outlier detection – the longitudinal (east-west) deviation discrepancies are larger than the latitudinal (north-south) differences.

Summary and Conclusion

In this short paper, we have used a recently released set of historic (pre-1966) astronomically observed vertical deviations to independently verify the AUSGeoid98-computed vertical deviations across Western Australia. Our results agree with earlier studies (*e.g.*, Jekeli 1999; Featherstone 2006), showing that vertical deviations are a useful independent validation of a gravimetric quasigeoid model, but the vintage of the astrogeodetic data, particularly in longitude/time, is a limiting factor.

We have shown that the AUSGeoid98-computed vertical deviations are generally of sufficient precision (one arc-second standard deviation) to support the reduction of terrestrial-geodetic survey data in Western Australia. A new Australia-wide gravimetric quasigeoid model is currently in preparation, awaiting the release of new datasets from dedicated satellite gravimetry, which should improve the situation yet further.

Acknowledgements: We would like to thank the three anonymous reviewers and editor for their very constructive critiques of this manuscript in a very short timeframe. WEF would like to thank the Australian Research Council (ARC) for funding research on the Australian quasigeoid and AHD through grants A49331318, A39938040, DP0211827 and my Australian Professorial Fellowship through grant DP0663020. Thanks also go to Jim Steed (Ret.) of Geoscience Australia and Dr Simon Holmes of SGT Inc. for providing some of the astrogeodetic vertical deviations. The figures in this manuscript were produced with the public-domain Generic Mapping Tools (Wessel and Smith, 1998; http://gmt.soest.hawaii.edu/). This is The Institute for Geoscience Research (TIGeR) publication number 61.

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Journal of the Royal Society of Western Australia, 90: 151–156, 2007

Feral Goldfish (*Carassius auratus*) in Western Australia: a case study from the Vasse River

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Manuscript received March 2007; accepted July 2007

Abstract

Minimal information is available with regard to impacts of wild populations of Goldfish; despite being one of the most widely introduced freshwater fishes of the world, and arguably the most popular ornamental fish species. During a control programme for a population of feral Goldfish in the Vasse River, Western Australia, aspects of population demographics and diet were examined. A relatively high growth rate was found with fish, on average, attaining ~ 180 mm TL at the end of their first year of life, a period that coincided with first maturity. Goldfish were relatively long-lived with the oldest fish recorded being in its 11th year of life. The diet was dominated by detritus that was largely comprised of blue-green algae. The potential of this species to exacerbate algal blooms within nutrient enriched environments is discussed.

Keywords: feral goldfish, *Carassius auratus*, Vasse River, Western Australia,

Introduction

The establishment of introduced fishes outside their natural range is often facilitated by a wide tolerance to environmental regimes, maximisation of reproductive potential, high genetic diversity and tendency for good dispersal mechanisms (r-strategists) (Stauffer 1984). An expression of a broad diet (*e.g.* omnivory) and the ability to tolerate degraded habitats also enables exotic species to exist and thrive in foreign environments. Within Australia, examples of omnivorous fish species that are highly adaptable to a wide range of environmental conditions include some of the poeciliids, cichlids and cyprinids; groups that are all traditional aquarium species but are naturally absent from the country (see Morgan *et al.* 2004). While the ecological impacts of some members of these groups are well understood, there is little information with regard to one of the most widely introduced freshwater fishes of the world, *i.e.* Goldfish (*Carassius auratus*). As arguably the most popular and well known ornamental fish species, it is not surprising that feral populations of Goldfish have been reported from almost every state of Australia (McKay 1984, Koehn & MacKenzie 2004) and indeed are now found throughout much of the world (*e.g.* Fuller *et al.* 1999, Gido & Brown 1999, Skelton 2001). It is also established in almost every state of the United States and is thought to be the first foreign fish species introduced into that country (*e.g.* Fuller *et al.* 1999). Goldfish have been implicated with the introductions of parasites to South Africa and Australia (Fletcher & Whittington 1998, Mouton *et al.* 2001, Hassan, Morgan, Beatty & Lymbery unpublished data) and with the decline of a number of native fishes in the U.S. (Deacon *et al.* 1964, Moyle 1976).

Within Western Australia, Goldfish are generally restricted to the south-western corner of the state in the vicinity of major population centres where they appear to be most successful in modified or degraded waters (Morgan *et al.* 2004). The only previous biological study (growth and feeding) of wild Goldfish populations in Australia was conducted by Mitchell (1979) who used scales to age fish from South Australia, while Izci (2001) determined growth rates and age and sex compositions for a wild population of Goldfish in Lake Eğirdir, Turkey. The main aim of this study was to implement an ongoing control programme for Goldfish in the highly nutrient enriched Vasse River and thereby reduce the biomass of the species. Secondary aims were to examine the distributions, habitat associations, age compositions and growth and diet of Goldfish and to develop an understanding of factors contributing to its success in this and other nutrient enriched waterbodies.

Methods

Study site

The Vasse River, in south-western Australia, is ~ 45 km long with a catchment of approximately 270 km^2. About 60% of the catchment is cleared and heavily modified, with much of the natural flows diverted to drainage canals for flood mitigation (Pen 1997). Much of the Vasse-Wonnerup estuarine lagoon, which is roughly 1.5 km wide and 25 km long, stretches behind narrow coastal dunes covering an area of 1000 ha, is cleared with the hydrology having been largely modified by drainage and tidal barriers and is threatened by eutrophication with the system no longer functioning as an estuary (Jaensch & Lane 1993, Pen 1997). Regardless, the system still provides important habitat for waterbirds and is

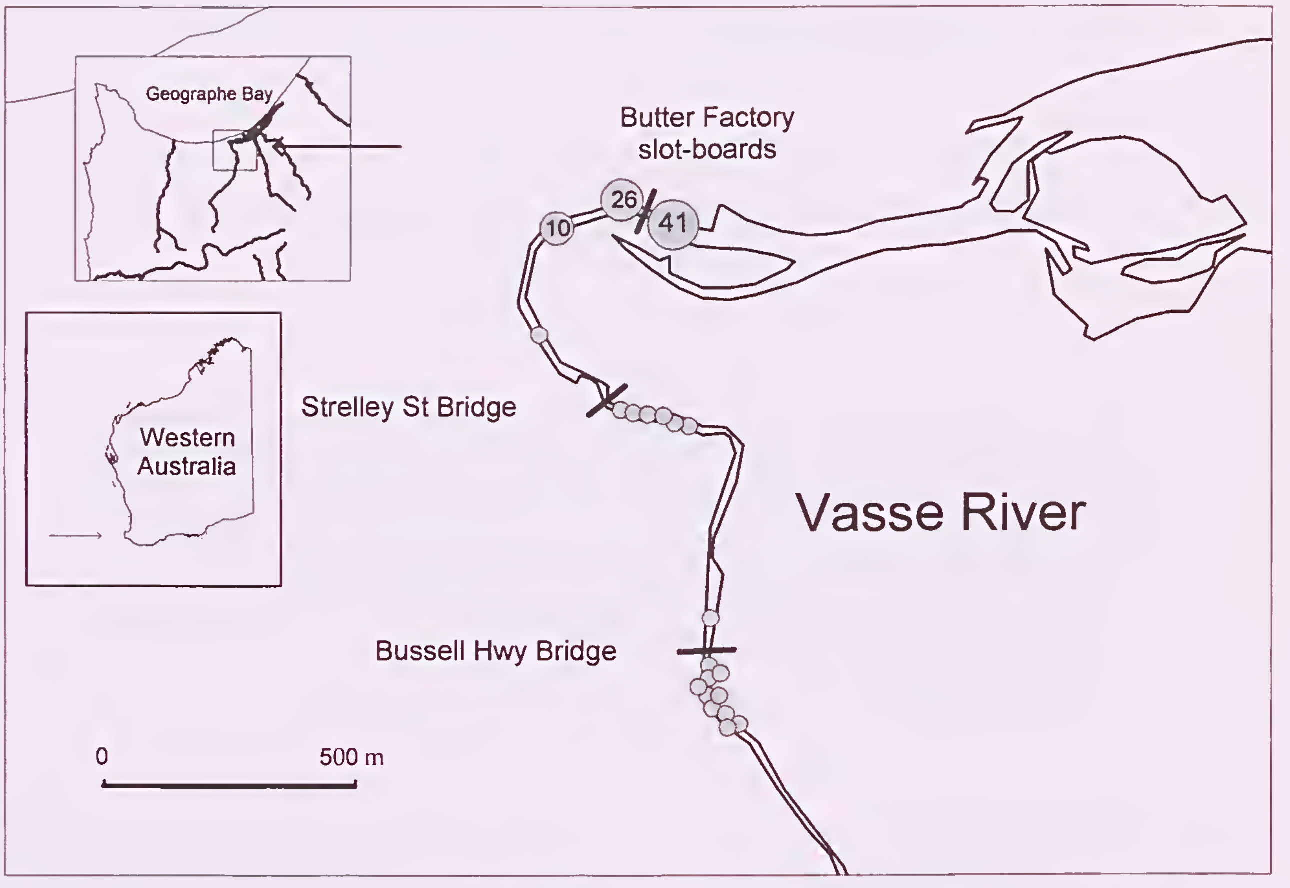

Figure 1. The location (and number) of Goldfish (*Carassius auratus*) captured in the Vasse River during March 2003 and December 2004. N.B. Catch locations remained consistent in subsequent years.

listed as a Ramsar Wetland of International Importance (Jaensch & Lane 1993, Pen 1997). In appreciation of the importance of natural stream morphology and riparian vegetation in creating healthy stream ecosystems, the Lower Vasse River Cleanup Program, coordinated by the Geographe Catchment Council, has undertaken reshaping and revegetation of the bed and banks of the Lower Vasse River while and conducting Phoslock™ trials to reduce dissolved phosphorus and thereby attempt to reduced blue-green algal (cyanobacteria) blooms in the river (Goss & Greenop 2003). During these works, the reported sightings and capture of feral fish such as Goldfish in the Vasse River has increased considerably in recent years.

Capture techniques

The distribution of feral Goldfish within the Vasse River was determined in December 2003 and March 2004, and goldfish removal events (for population control [see below]) occurred during March 2005, May 2006 and September 2006. Although sites were sampled throughout the catchment, Goldfish were restricted to the lower Vasse River (see Figure 1). As the lower Vasse River is a large body of water relative to upstream reaches due to slot board insertion and the Vasse River Diversion Drain, a number of methods were employed to capture as many Goldfish as possible. This initially involved the use of gill nets, seine nets and a back-pack electrofisher (a device that momentarily stuns fish). However, the subsequent Goldfish captures were achieved utilising a 240 volt, generator-powered electrofisher deployed from a boat. The entire stretch of the river from ~ 500 m upstream of the Bussell Highway Bridge to immediately downstream of the Old Butter Factory slot-boards was electrofished at least twice on each sampling occasion with the exception of December 2003 (see Figure 1). Key Goldfish habitats were revisited on each sampling occasion (see results). The latitude and longitude of each Goldfish capture was recorded using a GPS and a map of the distribution of Goldfish captures was produced using the MapInfo™ program.

Biological techniques

Each Goldfish captured was placed immediately in an ice slurry and, upon return to the laboratory, measured to the nearest 1 mm total length (TL) and weighed to the nearest 1 mg. A length-weight relationship was produced via testing a number of models and the one that provided the greatest R^2 value adopted as the best fit of the data. The stomach contents of a sub-sample of 20 Goldfish from a wide size range were removed and the contents classified into a number of prey categories. The frequency of occurrence and points method (Ball 1961, Hynes 1950) was used to food items in the stomachs of Goldfish and the relative contribution (by volume) of each prey category to their diet.

For age determination, the otoliths of each Goldfish in

all larger fish and the majority of the apparent juvenile (0+) fish were removed, immersed in methyl salicylate and viewed though a dissecting microscope using reflected light. The number of translucent zones was counted and it was assumed that these corresponded to year classes (while not specifically validated, this technique has been validated for the majority of native freshwater fishes in south-western Australia and for an introduced fish in the region (*e.g.* Morgan *et al.* 1995, 2000, 2002)). A length-frequency distribution was produced separately for those Goldfish captured on each sampling occasion.

The length of each individual Goldfish was plotted against its age and a growth curve fitted using a von Bertalanffy growth equation with October 1 as an estimated birth date. This estimate was made from the small size of individuals captured in December and from the capture of larval (newly-hatched) Goldfish in other parts of south-western Australia during early spring. The von Bertalanffy growth curve is $L_t = L_\infty[1\text{-}E^{-K(t-t_0)}]$, where L_t is the length at age t (years), L_∞ is the asymptotic length of the population, K is the growth coefficient and t_0 is the hypothetical age at which the fish would have zero length.

Results

Distribution, population structure and growth of Goldfish in the Vasse River

Goldfish were only captured in the lower sections of the Vasse River and none were captured in the Diversion Drain or upper catchment. Large numbers of juveniles were captured around the Old Butter Factory slot-boards and other structures such as bridges, while the larger individuals were usually found in the close vicinity (usually just upstream) of structures such as bridges or around snags (Fig. 1).

Analysis of length-frequency histograms and the number of translucent zones on the otoliths as an estimate of age (*e.g.* one zone = 1 year old, two zones = 2 year old etc.) revealed that the population of Goldfish in 2003 and 2004 in the Vasse River at the time of sampling was dominated by the cohort born in the spring of 2003 (Fig. 2). However, two older and larger fish, over 400 mm TL, were captured. During March 2005, a total of 105 Goldfish were captured. Approximately 76% of these belonged to the 0+ age class, *i.e.* they were in their first year of life. The remaining fish varied in age with the oldest being in their sixth year of life (*i.e.* 5+). During sampling in May 2006, 55 Goldfish were captured, with 84% belonging to the 0+ age class, one fish of 11 years, and another two older than 7 years. The majority of fish were captured at the Strelley Street Bridge (31, all 0+), while 15 were captured at the Vasse Bridge, six near the Bussell Highway Bridge and two at the Butter Factory slot-boards. During September 2006 no Goldfish were captured in the study area main channel. This, together with large reductions in our captures at the Bussell Highway Bridge and at Butter Factory, suggests that the control programme may have been successful in reducing the population; however, four Goldfish were captured in a wetland (New River Wetland) adjacent

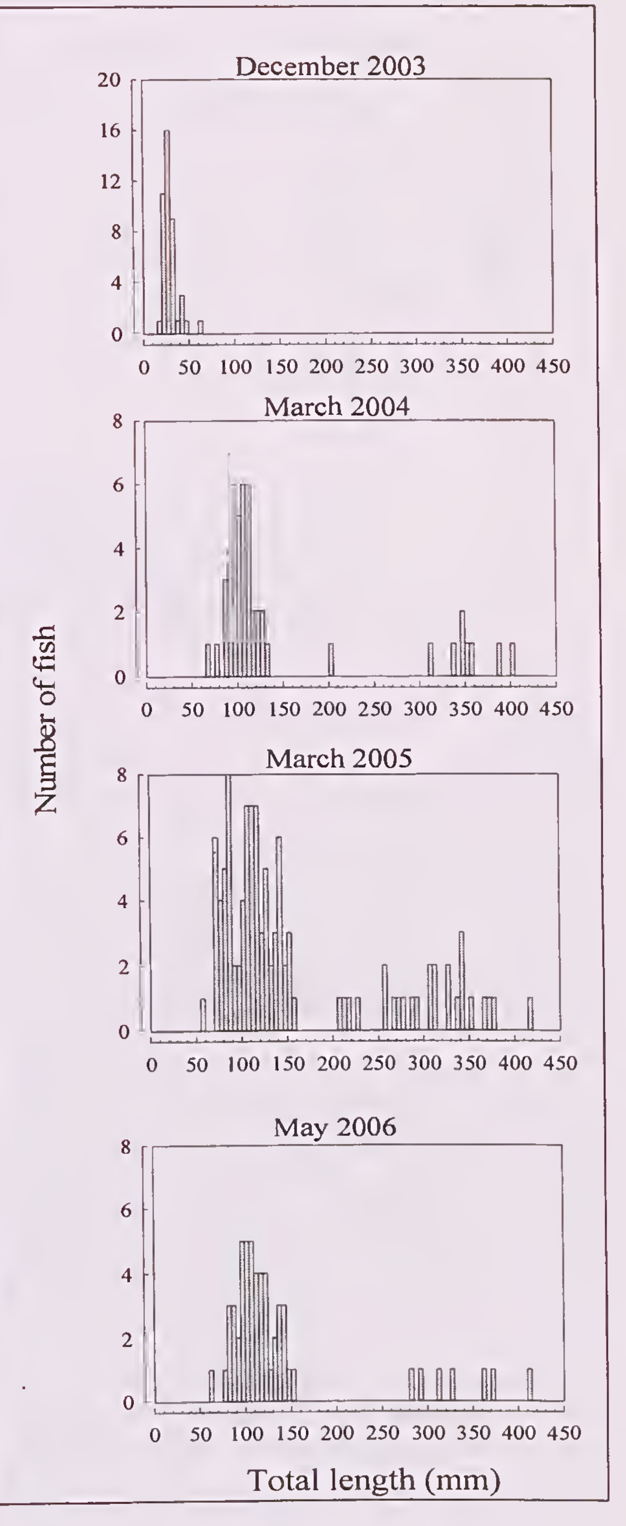

Figure 2. Length-frequency histograms of Goldfish captured in the Vasse River during December 2003, March 2004, March 2005 and May 2006.

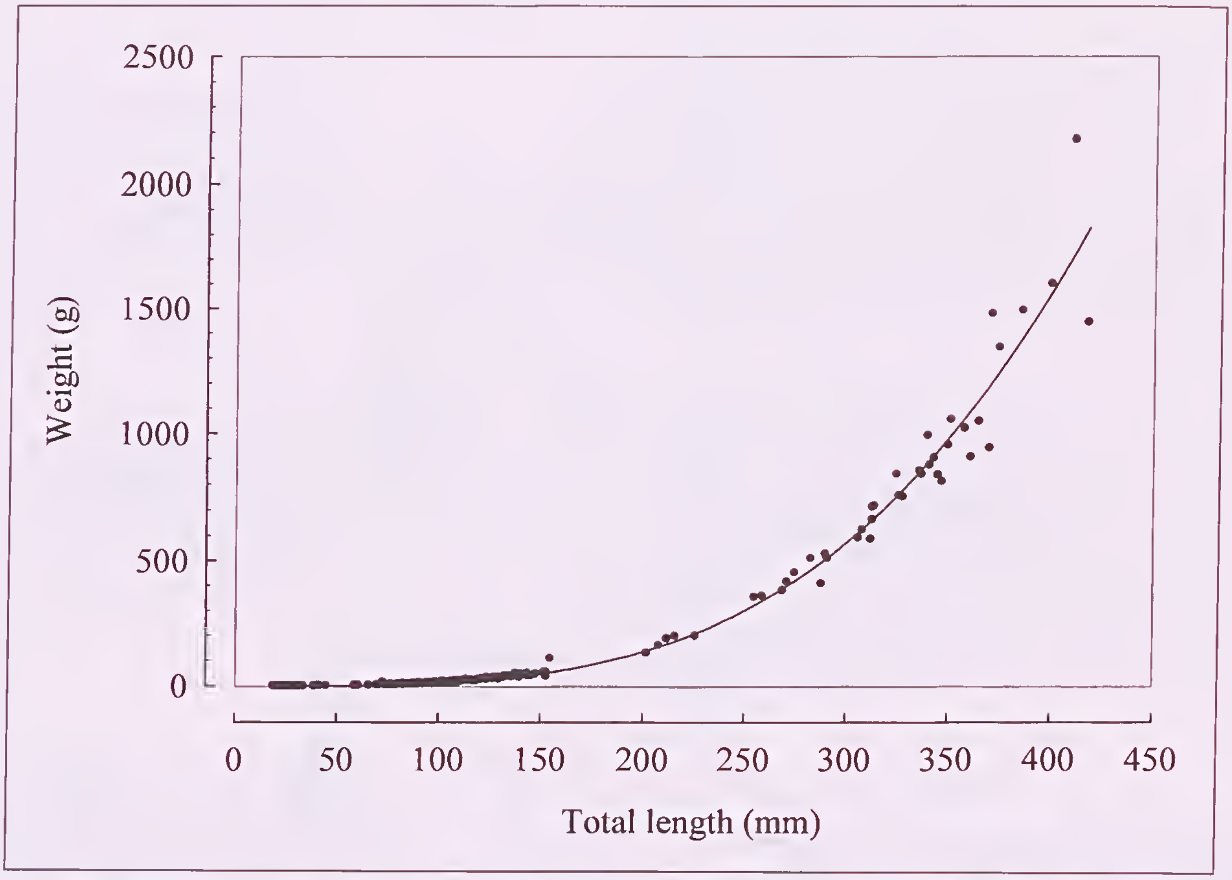

Figure 3. Length-weight relationships of the Goldfish captured in the Vasse River during December 2003, March 2004, March 2005 and May 2006. In the given equation, W = weight (g) and TL = total length (mm) of the fish.

and connected to the main channel. This wetland has only seasonal connectivity to the main channel and thus management actions should be undertaken to ensure that it does not act as a recruitment source of Goldfish.

The length-weight relationship for Goldfish in the Vasse River is:

$W = 1.168(10^{-6})(TL^{3.5077})$, where W = the wet weight (g) of the fish and TL = the total length (mm) of the fish (Fig. 3).

The von Bertalanffy growth equation is $L_t = 374.26[1-e^{-0.651(t-0.0163)}]$, where L_t is the approximate length at age t (in years). von Bertalanffy variables are: K = 0.651, $t_0 = 0.0163$ and $L\infty = 374.26$. Based on this equation, Goldfish at age 1 year in the Vasse River attain approximately 177 mm TL, whereas at ages 2, 3, 4, 5 and 6 they reach ~ 271, 321, 346, 356 and 367 mm TL, respectively (Fig. 4).

The largest fish captured was 411 mm TL and weighed approximately 2.2 kg and was in its eighth year of life. The higher proportion of larger fish captured during 2005 was probably a result of the lower water levels encountered due to removal of the slot boards at the Old Butter Factory which are usually inserted to artificially maintain water levels.

Many of the larger fish had gonads that had clearly spawned and are classed as 'spent'. Examination of some of the 0+ cohort (6 month old fish) revealed that gonadal development was commencing and that they would have spawned at the end of their first year of life.

Diets and ecological impact of Goldfish in the Vasse River

The stomach contents of 20 Goldfish (28–386 mm TL) examined from the Vasse River were dominated by detritus that was largely comprised of cyanobacteria (blue-green algae), but additionally contained diatoms, nematodes, anisopteran larvae, coleopteran larvae, dipteran larvae, eastern mosquitofish, green algae and some terrestrial insects.

Community engagement

An approach identified by Koehn & MacKenzie (2004) as important in the management of feral fishes includes not only the recognition of pest species by managerial and government organisations but it is important to engage the scientific and community sectors in all aspects of the process. The recognition of feral Goldfish populations as a threat to ecosystem health in the Vasse River, at least, has been accepted, largely as a result of the involvement of managerial organisations such as Geocatch, Fisheries WA, the Vasse-Wonnerup LCDC, combined with community participation and wide local media coverage.

Discussion

The age and growth analyses of Goldfish in the Vasse River demonstrated substantial growth rates compared to populations elsewhere. The only previous age and

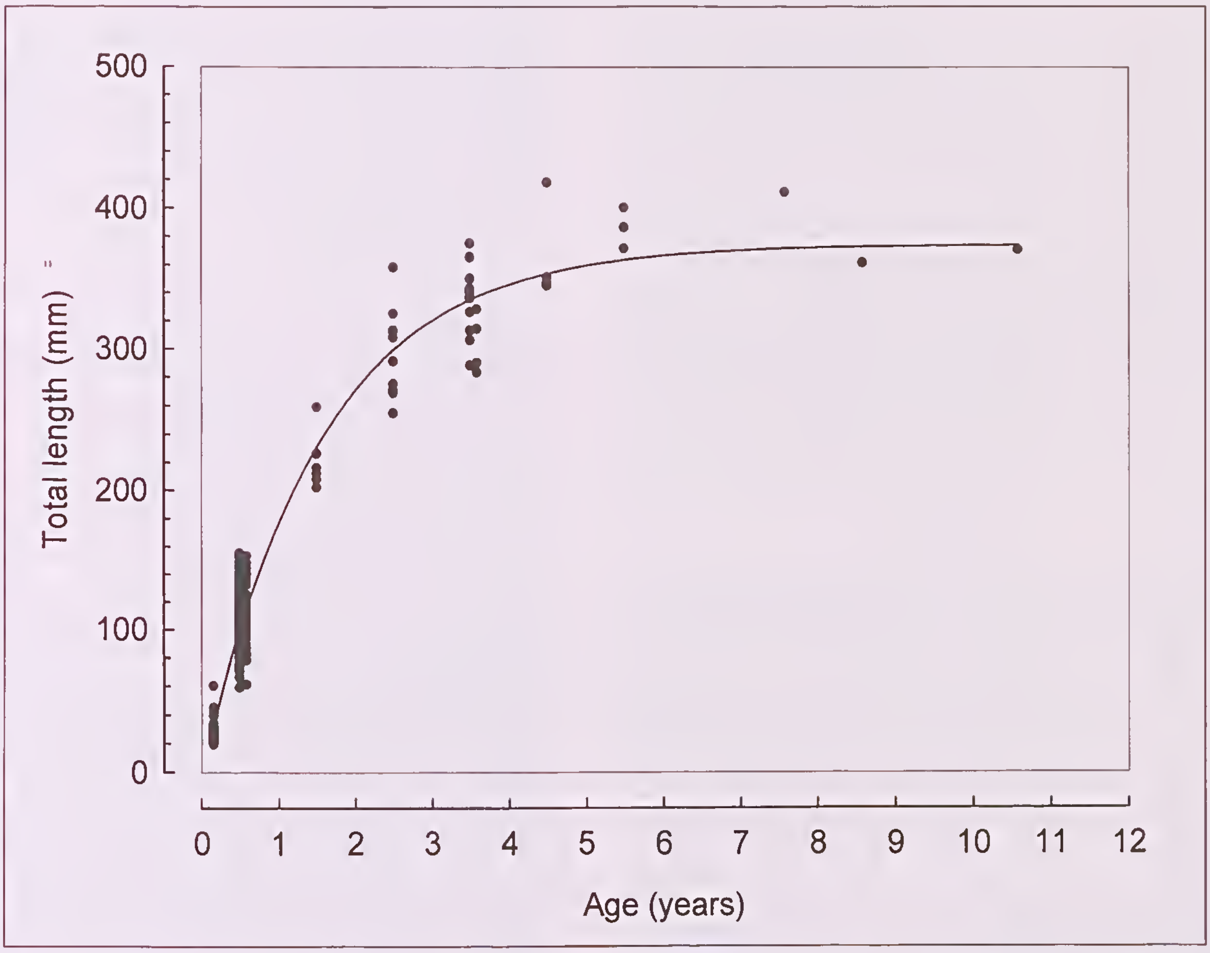

Figure 4. Total length at age of Goldfish captured during the study in the Vasse River including the von Bertalanffy growth curve. N.B. approximate age classes were based on the number of translucent zones on the otoliths and October 1 was assigned as the birth date. K = 0.651, t_0 = 0.0163, L∞ = 374.26.

growth study on wild Goldfish populations in Australia was by Mitchell (1979) who used scales to age fish from South Australia. The growth rates here substantially exceed those in Mitchell's study and are similar but higher to those published by Izci (2001) for a wild population of Goldfish in Turkey. Mitchell (1979) found one fish living for over 10 years that weighed over 2 kg. From the length-weight relationship in the Vasse River it is predicted that Goldfish would attain 2 kg at 447 mm TL.

Kolmakov & Gladyshev (2003) demonstrated that significant growth of the cyanobacteria *Microcystis aeruginosa* is stimulated by the passage through Goldfish intestines, while other cyanobacteria such as *Anabaena flos-aquae* and *Planktothrix agardhii* that were passed through Goldfish guts exhibited greater growth compared to the controls. The process of cyanobacteria stimulation is not known, however the authors considered that the passing through the Goldfish gut may give nutrient enrichment or that mechanical re-agglutination of cells from colonies may occur. *Microcystis* sp. and *Anabaena* sp. are known to cause algal blooms in the Vasse River. The above findings of the diets of the Goldfish in the Vasse River, together with the fact that they are known to stimulate significant growth in blue-green algae, is cause for concern in a system that is currently exposed to severe algal blooms during spring, summer and autumn (see Paice 2001). Thus, a substantial increase in Goldfish biomass could become a major factor attributing to algal blooms in the Vasse River and indeed within nutrient enriched environments elsewhere. Furthermore, the vigorous bottom feeding methods of Goldfish resuspends nutrients making them available to algae. Within the Vasse River algal blooms have lead to a number of fish kills since 1997 (Paice 2001), a period after the initial introduction of Goldfish, noting that during 2006 we captured a 10 year old fish. An increase in algae provides this feral species with an abundance of a food source that they can utilise from a very young age. The high growth levels found in Goldfish within the Vasse system may be a combination of the high degree of food availability and warmer conditions provided by the diversion of flows around this system creating a lentic rather that lotic environment.

Feral Goldfish have the potential to prey on the eggs, larvae and adults of native fishes and have been known to cause declines in native fish populations in the U.S. (e.g. Deacon *et al.* 1964). Goldfish compete with native fishes for food and space and by growing to a much larger size than all but one of the native freshwater fishes in the region, they would escape predation from a young age (probably by a few months old they would attain

lengths larger than can be consumed by native fishes). Goldfish, as a benthic generalist/herbivore, has been shown to cause increased turbidity and deplete aquatic vegetation (Richardson *et al.* 1995). A reduction in aquatic vegetation reduces habitat and potential spawning sites for native fishes.

Very little is known of the parasites infecting freshwater fishes in Western Australia; however it is acknowledged that non-native parasites may use introduced fishes as vectors to infect native fishes. Goldfish are known carriers of a number of serious diseases and have been implicated with the introduction of several fish pathogens in South Africa (Mouton *et al.* 2001) and at least one monogenean trematode in Australia (Fletcher and Whittington 1998). Screening of parasites and diseases within captive populations of Goldfish is crucial in the detection of potentially harmful organisms.

The implications for the activation of cyanobacteria blooms after passing through fish digestive tracts are serious when considering the widespread distribution of Goldfish throughout the world, where they are predominantly associated with urban areas. A number of other fishes that have been introduced throughout the world, including within Australia, consume phytoplankton and thus have the potential to stimulate cyanobacteria growth in nutrient enriched environments. Specifically, feral populations of Tilapia (*Oreochromis mossambicus*), One-spot Livebearers (*Phalloceros caudimaculatus*), Swordtails (*Xiphophorus helleri*) and Carp (*Cyprinus carpio*) are not only established within Western Australia (Morgan *et al.* 2004), but most of these species have been introduced throughout the world. The control of algal blooms may be aided with eradication programs of feral detritivorous fishes inhabiting nutrient enriched environments worldwide.

Acknowledgements: Funding and project partners for this project included Geocatch, Fishcare WA, Fisheries WA and the Vasse-Wonnerup Land Conservation District Committee. There was also strong community involvement and support for the project and in particular we would like to thank Gilbert Stokman, Veronica Piper, Annaleisha Sullivan, Dane Hordacre, Michael Burgess, John McKinney, Jenny Mitchell, Craig Astbury, Howard Gill and Dan French.

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Notes on ....

A substantial recruitment year for the western yellowfin bream (*Acanthopagrus latus*, Sparidae) sustains years of high catch rates in the inner gulfs of Shark Bay, Western Australia

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Manuscript received January 2007; accepted June 2007

Abstract. A large increase in the annual commercial catch and catch per unit effort of western yellowfin bream (*Acanthopagrus latus*) in the inner gulfs of Shark Bay, Western Australia, from 2002 to 2005 prompted an examination of the age structure of the 2005 catch. Sectioned otoliths from 108 fish were assessed to determine whether the cause was related to an increased abundance following a substantial recruitment. The 1999 age class was exceptionally strong, contributing 48.1% of the sample, and according to published growth rate estimates, this cohort would have recruited to the fishery at the same time catch rates began to increase. Year class strengths of older cohorts were consistent with catch sampling carried out in 1999 and 2000, together demonstrating highly variable interannual recruitment, a trait commonly reported for sparids. Neither Leeuwin Current strength nor rainfall was found to be associated with year class strength. Factors determining and possibly predicting year class strength in this species in Shark Bay remain unknown and require further research.

Keywords: recruitment; western yellowfin bream; *Acanthopagrus latus*; Shark Bay; otolith; year class strength, age

Introduction

Shark Bay, Western Australia, is a World Heritage Property with a complex marine embayment (Fig. 1) in a semi-arid to arid climate (Francesconi & Clayton 1996). The commercial fishery for western yellowfin bream (*Acanthopagrus latus*, Sparidae) in the inner gulfs forms part of the Shark Bay Beach Seine and Mesh Net Managed Fishery (Norriss & Jackson 2006). Commercial fishers are legally required to submit catch and effort data to the Western Australian Department of Fisheries, declaring the weight and species composition of their catch each month, and number of days fished (effort). In 2002, the total annual commercial *A. latus* catch, and catch per unit effort (CPUE), began to increase (Fig. 2). In 2003, 2004 and 2005 the catch and CPUE further increased to about 2.5 times the long-term annual average, prompting an investigation into the reasons for this increase, which was either due to a change in behaviour of fishers related to increased targeting and/or fishing efficiency and/or a proliferation in abundance following highly successful recruitment to the fishery.

Growth rates for Shark Bay *A. latus* estimated by Hall *et al.* (2004) suggest that the year class spawned in 1999 would have dominated recruitment to the 250 mm minimum total legal length for the fishery during 2002, the year when catch and CPUE began to increase. We therefore tested the hypothesis that the increased catch and CPUE was due to a proliferation in abundance dominated by the 1999 year class.

Methods

During 2005 a sample of 108 commercially-caught *A. latus* were collected from the local fish factory at Denham, Shark Bay, the only port of landing for the product. Catches from multiple fishers on several occasions were taken to ensure the sample was representative of the *A. latus* population in the fishery. Sagittal otoliths were removed, sectioned and examined microscopically under reflected light (Fig. 3). Their opaque zones are formed annually (Hall *et al.* 2004), and there is a short, distinct spawning period during late winter and early spring (Hesp *et al.* 2004), enabling

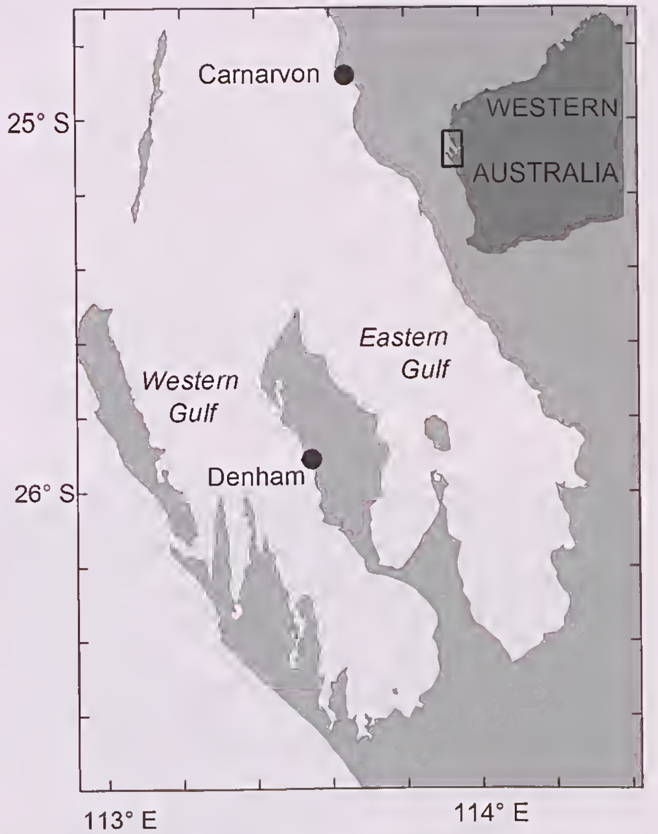

Figure 1. Map of Shark Bay, Western Australia, where the Shark Bay Beach Seine and Mesh Net Managed Fishery occurs predominantly in the inner gulfs (Eastern and Western) south of latitude 25°30' S.

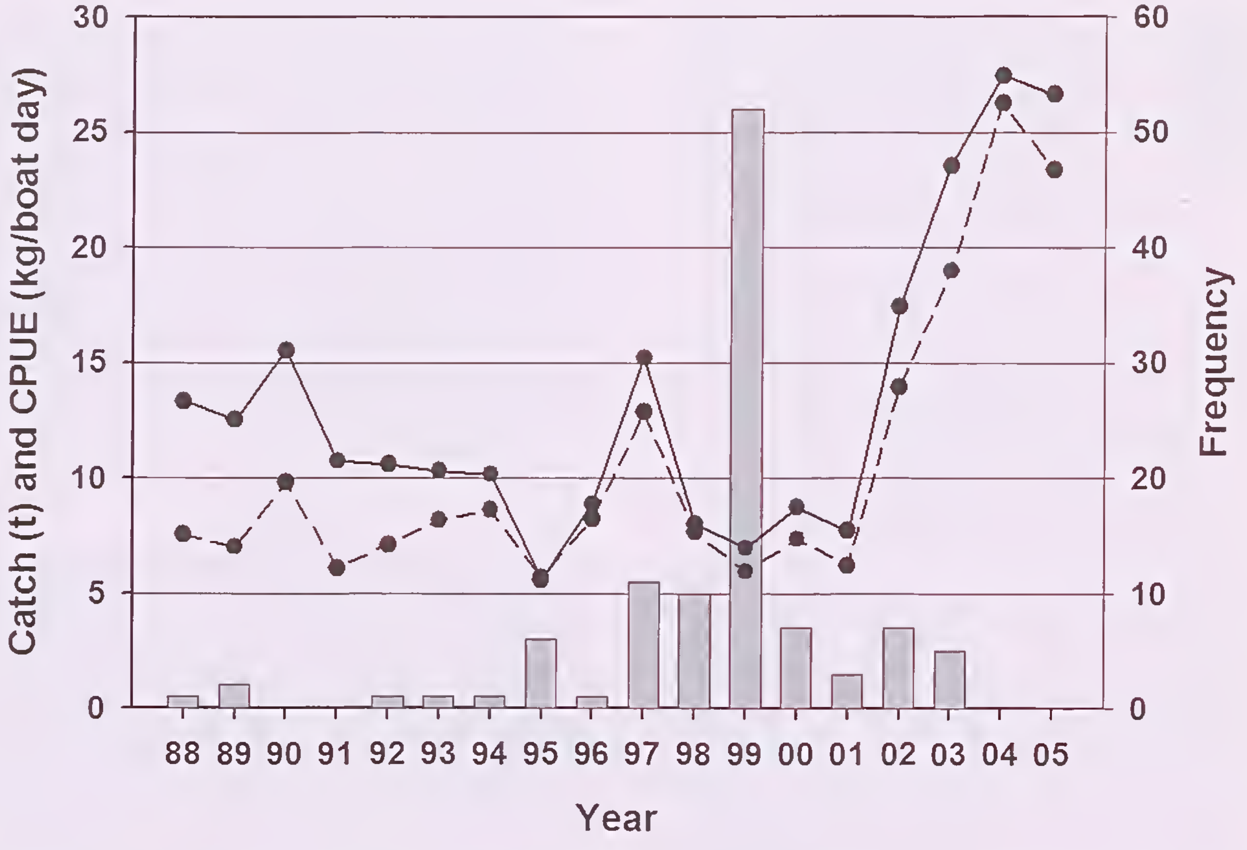

Figure 2. Total annual catch (solid line) and catch per unit effort (dashed line) for Shark Bay *A. latus* each calendar year (source: CAES, Dept. Fisheries, WA), and the frequency of individuals in each year class (bars) from a commercially-caught sample (n=108) collected in 2005.

accurate aging of individuals. We could thus allocate the year of birth to each fish and assess the relative abundance of each year class in the catch sample.

Results and Discussion

A very strong 1999 year class was observed, comprising 52 (48.1%) of the 108 fish that we sampled (Fig. 2). Based on age and growth parameters estimated by Hall *et al.* (2004), the mean total length of the 1999 year class as at 1 January 2002 was 215 mm (95% c.i. 208 to 221), and at 31 December 2002 was 271 mm (95% c.i. 261 to 279). With a minimum legal length of 250 mm, the 1999 year class would have recruited to the fishery during 2002, consistent with the limited increase in catch and CPUE that year. The elevated catch and CPUE in 2003 and 2004 was consistent with full recruitment of this highly abundant year class to the fishery in those years. The dominance of the 1999 year class in our sample, together with the timing of the increased catch and CPUE, constitutes strong evidence that the high

Figure 3. Cross section of a Shark Bay *A. latus* sagittal otolith from the 1999 year class, caught in 2005. Opaque zones (arrowed) are formed annually. Reflected light; scale bar = 1 mm.

catch and CPUE was caused by an increased abundance of fish available to fishers generated by recruitment of the strong 1999 year class to the fishery. Although increased targeting by fishers and/or fishing efficiency cannot be totally excluded in this multi-species fishery, the strength of the 1999 year class has been a major influence.

The 1995 year class also exhibited relatively strong recruitment (Fig 2), confirming a similar observation by Hall *et al.* (2004) from commercial catch samples from 1999 and 2000. This suggests that all three samples provided consistent and representative age structures of the population. The 1995 year class was not associated with an increase in catch or CPUE, indicating that such an increase requires particularly strong recruitment like the 1999 year class. Hall *et al.* (2004) also found a strong 1990 year class which we failed to detect, although these very old fish may have almost disappeared from the population by the time we sampled in 2005.

Catch-at-age sampling shows that interannual recruitment is highly variable, a common feature of sparids worldwide (e.g. Azeta *et al.* 1980; Geoghegan & Chittenden 1982; Francis 1993; Vigliola *et al.* 1998; Hamer & Jenkins 2004), sometimes affecting catch and CPUE (McGlennon *et al.* 2000). In temperate southern Australian estuaries, variability in year class strength for the congeneric *A. butcheri* is associated with rainfall and river flow, in turn influencing catch and CPUE (Norriss *et al.* 2002). There was no known rainfall event in arid Shark Bay associated with the 1999 *A. latus* recruitment, however.

Water temperature is strongly correlated with year class strength in the sparid *Pagrus auratus* in New Zealand (Francis 1993). Along the West Australian coast the warm, southward-flowing Leeuwin Current is a major oceanographic feature affecting recruitment of fish and invertebrates (Caputi *et al.* 1996), including the northern waters of Shark Bay (Joll & Caputi 1995). Sea levels, an index of Leeuwin Current strength, at nearby Carnarvon indicate no distinctive timing or feature of the current that might explain the 1999 *A. latus* recruitment event. Moreover, the penetration of the current into the shallow inner gulfs, where the *A. latus* fishery operates, appears minimal based on hydrodynamic modelling (Nahas *et al.* 2003) and the existence of frontal systems (transitional regions between mixed and stratified water columns) around the entrances of Shark Bay (Nahas *et al.* 2005).

Intertidal mangrove creeks in Shark Bay are an important habitat for juvenile *A. latus* (Hesp 2003), and possibly a key to determining year class strength. Relative to other years 1999 had a distinct lack of very low tides in Carnarvon in the months following spawning. No relationship is apparent between tides and year class strength among other years, however. Key factors determining and possibly predicting year class strength for this sparid remain unknown and require further research.

Acknowledgements: We thank the commercial net fishers of Shark Bay, John Standring at the Denham Fish Factory, and Kim Gray for collecting and forwarding samples. Carnarvon sea level data was supplied by the West Australian Department for Planning and Infrastructure.

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Notes on ....

Measurement of Southern Brown Bandicoot (*Isoodon obesulus*) body temperature using internal and external telemeters

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Manuscript received January 2007; accepted June 2007

Abstract. Two types of external temperature telemeter were designed and tested for their accuracy in measuring body temperature of southern brown bandicoots. Three attachment sites (groin, armpit and base of tail) and a number of methods of attachment were tested. The most effective was attachment to the base of the tail with surgical tape. Accuracy of external body temperatures was tested against data obtained from a surgically-implanted telemeter. External temperatures measured by telemetry did not accurately reflect core body temperature, but were instead closer to ambient temperature. As such, external telemetry is not recommended for use with animals of this size (~ 1000 g).

Keywords: Body temperature telemetry, bandicoot, external telemeter, circadian rhythm.

Introduction

Measurement of body temperature (T_b) is fundamental to studies of mammalian physiology and is of prime importance in assessing the thermal responses of animals which may exhibit heterothermy (Brown & Bernard 1991; Dausmann 2005). The most common method of T_b measurement is via the insertion of a rapidly responding thermocouple or thermistor into the cloaca or rectum. Although accurate if performed correctly, this method requires the study species be captured and handled. Such procedures can be stressful for the study species and therefore may result in elevated T_b. Further, the technique does not allow for continual remote measurement of T_b in free-ranging species (Brown & Bernard 1991; Audet & Thomas 1996). To combat this limitation, some researchers use surgically implanted telemeters to remotely monitor T_b (Muchlinski *et al.*; 1998; Refinetti 1999; Geiser & Drury 2003), however, this method also has it drawbacks. The most important is that implantation of telemeters requires the study animals to undergo at least one surgical procedure. This can be stressful and cause infection, both of which can alter thermoregulatory patterns. Surgical implantation also reduces the signal transmission distance of the telemeter (as the signal must pass through the body wall), which is important in studies of highly-mobile species (Audet & Thomas 1996; Barclay *et al.* 1996).

To both measure T_b remotely and avoid surgery related difficulties, external attachment of body temperature telemeters have been used on a number of species of endotherms (Audet & Thomas 1996; Barclay *et al.* 1996; Körtner & Geiser 2000; Körtner *et al.* 2001; Dausmann 2005). In these studies, small telemeters were either glued to the experimental animals, attached using an elastic harness, or as a collar. Individual studies have had mixed results, largely depending on the size of the subject species. External T_b telemetry worked well with small sized animals (~ 20–100 g) where skin temperature (T_{sk}) was close to and linearly correlated with T_b (Audet & Thomas 1996; Dausmann 2005). However, in larger animals (380–550 g) the difference between T_{sk} and T_b increased by several degrees (Körtner *et al.* 2001). The only time external T_b telemeters have been used on a mammal greater than 600 g was by Dawson & Bennett (1978), who measured pouch temperature at moderate ambient temperatures (T_a) for a single female spectacled hare wallaby (*Lagorchestes conspicillatus*; average mass 2660 g). In this experiment T_{pouch} was approximately 0.4–0.7°C lower than the simultaneously measured rectal temperature.

This study tested the validity of using externally attached temperature telemeters for measurement of T_b for captive southern-brown bandicoots (*Isoodon obesulus*). Data were compared to measurements of T_b obtained using a surgically implanted telemeter.

Materials and Methods

Two adult male *I. obesulus* were studied at the University of Western Australia. During study, bandicoots were maintained in sheltered outdoor enclosures or controlled temperature rooms (CTR) depending on the experiment and were provided with food and water *ad libitum*.

Two types of single-stage FM external T_b telemeters were custom made for this study (Titley Electronics, Ballina, Australia and Sirtrack Wildlife Tracking Equipment, Havelock North, New Zealand). Both were < 20 mm x 15 mm x 10 mm in size and weighed < 3 g. Both had internal loop antennae and transmission longevity of ~ 3 months. Prior to use, both telemeters were calibrated by placing them in a water bath at various temperatures (measured by a reference mercury thermometer) and recording their pulse rate. The temperature of the water bath was increased in intervals of 2°C every thirty minutes between 10 and 45°C. Exponential equations relating telemeter frequency and temperature were calculated. Telemeters were initially used to test attachment sites (groin, armpit and base of the tail) and methods (including surgical tape and glue) on one bandicoot (mass 1035 g). These particular attachment sites were chosen as it was thought that T_{sk} at these sites would be closer to core T_b. Then, one telemeter was coated in purified beeswax and surgically implanted into another study animal (mass 1160 g). For implantation, the bandicoot was anaesthetised with 4% (induction) and 1% (maintenance) halothane. The abdomen was incised

and the telemeter inserted into the peritoneum. The incision was stitched and the animal left in a CTR at 28°C for 2 weeks to recover. Another telemeter was attached to the base of the tail of the same animal using surgical tape for comparison between external and internal telemetry data. This bandicoot was placed in a CTR on a 12 hour light:dark cycle. The room was set to 10°C (night) / 20°C (day) for one week (Cycle 1) then 20°C (night) / 30°C (day) for one week (Cycle 2) to test the influence of T_a. After this time, the bandicoot was returned to its sheltered, outdoor enclosure and T_b was measured again for approximately 2 weeks. These data are shown in Figure 1.

Telemetry data were recorded using an AR8000 radio receiver, CU8232 interface, antenna and personal computer running AR8000 Temperature Telemeter Logging Companion (© 1997 Stig O'Tracey Spiney Norman Systems). Raw data were exported to MS Excel for conversion and analysis.

Results

Attachment of external telemeters proved to be difficult at all sites, with the base of the tail proving the best in terms of attachment duration, lowest discomfort for the experimental animals, and greatest signal strength. Attachment in the groin or armpit using surgical tape inhibited the normal movement of the bandicoots and individuals were easily able to reach these sites to remove the telemeter (reducing attachment time to less than 24 hours). Telemeters stayed attached to the tail for 5 to 14 days.

A distinct daily pattern in T_b was observed for *I. obesulus* based on the data from the surgically implanted telemeter (Fig. 1). Under Cycle 1, the average core T_b measured was 36.8±0.1°C (max 39.7°C, min 32.6°C, n = 4547). Both the highest and lowest T_bs generally occurred in the early hours of the morning (Fig. 1). During the inactive phase (0600 to 1800 hrs), T_b was more stable than during the night (1800 to 0600hrs – active phase); however, there was no difference in average T_b between day (37.8 ± 0.1°C) and night (37.3 ± 0.1°C) throughout the controlled temperature study. Under Cycle 2, average T_b was 36.0 ± 0.2°C (n = 2502). Base of the tail external telemetry data appeared to simply mirror T_a throughout both trials. Under Cycle 1, average T_{sk} was 17.8 ± 0.1°C (max 25.8°C, min 13.6°C, n = 2041). The inactive phase T_{sk} (19.3 ± 0.1°C) was marginally higher than the active phase T_{sk} (16.5 ± 0.1°C). Inactive phase T_{sk} (19.3°C) was virtually identical to T_a during that time. Under Cycle 2, average T_{sk} was 26.8 ± 0.1°C. Once again, the inactive phase T_{sk} (26.5 ± 0.2°C) was only marginally higher than the active phase T_{sk} (24.3 ± 0.2°C).

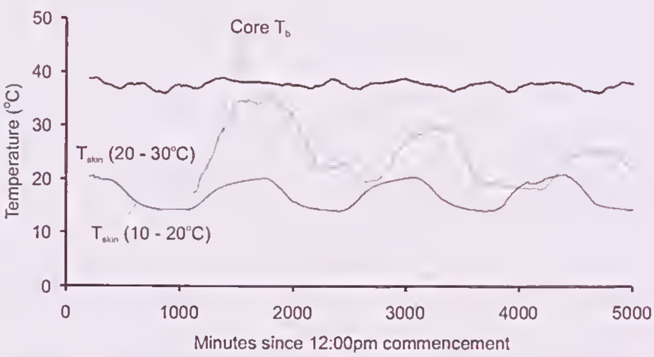

Figure 1. Body temperatures of a single male southern brown bandicoot. Black line = core T_b measured by a surgically implanted telemeter for a bandicoot under ambient conditions; dark grey line = external telemetry data under a 10–20°C temperature cycle; light grey line = external telemetry data under a 20–30°C cycle.

Discussion

Most previously trialled methods of attachment of external telemeters were deemed inappropriate in this study as (i) bandicoots are large enough for the thermal gradient between T_{core} and T_{sk} to become an issue if the telemeter was attached at any site except the most insulated, (ii) I wanted to be able to remove and reattach the telemeters easily and (iii) male (pouchless) animals were used. The resources to custom manufacture specialised telemeter attachment devices were not available, so surgical tape was used as the method of attachment. This was because it is cheap, simple to use, is easily removable and will fall off on its own after a while (important in the field). The 'armpit', groin and base of the tail were used, with the base of the tail proving the best in terms of ease of attachment / removal, strength of signal, reduced bandicoot discomfort and duration of attachment. The fact that base of the tail external telemetry data appeared to simply mirror T_a throughout both trials suggests that the gradient between T_{sk} and T_b for a mammal of this size (ie over ~ 1000 g) is too great and that external body temperature telemetry is not viable for species of this size.

Average T_b measured using internal telemetry was marginally higher than previously reported T_bs of resting bandicoots at 30°C (33.7 ± 0.2 to 36.1± 0.1°C; Hulbert & Dawson 1974; Withers 1992, Larcombe & Withers 2006) and the resting T_b of *I. obesulus* at 30°C (35.0 ± 0.1°C; Larcombe 2002). The slightly higher T_b measured here was expected, as the bandicoots were not resting when T_b was measured, but instead continued their normal activity. Increased activity results in an increase in T_b (Brown & Dawson 1977). The mean T_b of the closely related northern brown bandicoot (*Isoodon macrourus*) under T_as of 12–22°C was 36.2°C (range 34.2 to 38.6°C), which is almost exactly the same as the 36.8°C measured in this study under Cycle 1 (Gemmell *et al.* 1997). Similarly, the maximum (38.6°C) and minimum (34.2°C) T_b measured for *I. macrourus* are close to those measured in this study (39.7°C and 32.6°C, respectively). This shows that *I. obesulus*, like *I. macrourus* has a relatively labile T_b, with the T_b of both varying by ~ 5°C daily.

The differences in T_bs measured in the active and inactive phases of the bandicoots natural circadian cycle can be explained by two factors. Firstly, a more stable inactive phase T_b may be because the animals were intermittently moving during the night/active phase. During the inactive phase, T_b would be expected to be fairly stable as the animals activity levels were relatively constant (ie while they slept) however, this constancy would be lost during the active phase as the animals would have varying levels activity depending on what

they are doing. Conversely, the slightly higher inactive phase T_b can be explained by the fact that the T_a when the bandicoots were inactive was up to 10°C higher than the active phase T_a.

I. obesulus displays a slight nychthermal variation in T_b. Hulbert & Dawson (1974) found no pronounced cycle in the body temperatures of five bilbies (*Macrotis lagotis*), however T_b was slightly higher at the beginning and end of the night and that the greatest variation in T_b was during the active phase. Brown & Dawson (1977) found that three species of kangaroo displayed a nychthermal variation in T_b of 1.6–3.1°C, and, generally, rectal temperature was highest in the late afternoon (end of the inactive phase) and lowest in and early morning. The chuditch (*Dasyurus geoffroii*) also had a higher and less variable T_b during the active phase (Arnold 1976). Conversely, Gemmell *et al.* (1997) noted a distinct daily pattern in T_b for several species of marsupial with T_b being higher during the active phase.

The results of this study indicate external temperature telemetry does not provide an accurate measure of T_b in the southern brown bandicoot, and as such it is not recommended for use with animals of this size (~ 1000 g). Further study on a larger sample size is needed to assess whether *I. obesulus*, and marsupials in general, actually exhibit circadian variation in T_b and, if so, what this variation is.

Acknowledgements: This project was funded by an APA Grant. Bandicoots were caught and held under license from CALM. This research was conducted with the approval of the UWA Animal Experimentation Ethics Committee. Thanks to Sasha Voss and Philip Withers for comments on the manuscript and Shane Maloney for the loan of the telemetry equipment and help with implantation surgery.

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Published on 26/09/2007 **Typeset and printed in Western Australia**